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ACOUSTICALLY SCANNED OPTICAL IMAGING DEVICES.

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ACOUSTICALLY SCANNED OPTICAL IMAGING DEVICES

I. SUMMARY

The aim of the work on this contract during the last six months has been to improve the technology of the optical imaging devices so that we can carry out more sophisticated studies of optical transform methods; and can make reproducible devices with reasonably uniform characteristics, so we need not spend a large amount of time with difficult problems of mechanical alignment. In addition, we have been concerned to eliminate the trapping problem in zinc oxide, to eliminate sideways diffusion of carriers generated by light, so as to keep a constant modulation transfer factor, and to eliminate problems with surface states in both airgap and ZnO devices.

We believe that we have, after a great deal of effort, been able to circumvent most of these difficulties and make viable convolver configurations, which eventually would be highly reproducible. A new type of airgap convolver has been made, which uses a number of thin rails 4 μm wide to separate the semiconductor from the piezoelectric substrate. This is a far simpler configuration than the post configuration used at Lincoln Laboratories.[1] The system has proved to be mechanically stable and reproducible. It has been possible to replace the silicon and obtain consistent results from run to run. We have developed broadband transducers and matching networks for both the airgap and ZnO on Si convolver. We have developed new p-n junctions arrays laid down in the Si, and also Schottky barrier arrays laid down on the Si. The use of these arrays eliminates surface state problems and problems with diffusion of generated carriers, parallel to the surface of the semiconductor. In addition, the Schottky barrier devices laid down under the ZnO on Si device and

tested on another contract have proved to eliminate problems with storage in the traps in the zinc oxide. Thus, we have eliminated the troublesome historesis effects associated with ZnO on Si.

The airgap device has been tested in a new configuration using rows of p-n junction diodes laid down in the silicon. A theory on the optical sensitivity has been developed and appears to be, at the present time, in qualitative agreement and partial quantitative agreement with the experimental results. The devices have proved to be very uniform along their length and they have been operated in the Fourier transform mode, using a new type of dispersive delay line to obtain the inverse transform. This dispersive delay line was supplied to us by Lincoln Laboratories. We have shown that we can obtain partial elimination of background illumination and of the dark signal by using a pulsed gate in the Fourier transformed output to eliminate the low spatial frequency components. At the present time, the measured resolution is 120 spots in 2 cm, i.e., about 180 μ. We would expect that, with incorporation of the grating filter explained in our earlier reports, we should be able to obtain the maximum resolution of the dispersive delay line filters of 250-300 spots.

We now have a good reproducible rf sputtering process for deposition of zinc oxide. We have also been working with a dc sputtering system, but have decided to continue, for the present, with the rf system as it is providing good reproducible results. We have designed a new ZnO on Si device with p-n junctions or Schottky barrier diodes laid down in the Si underneath the ZnO. This device will be a first step towards a two-dimensional transform device. We expect that, within the next six months, we will be testing a simple form of a device which will provide a raster scanned output of a two-dimensional optical transform. The theory of

this device has been developed and it appears to indicate that we should be able to obtain resolutions comparable to the linear devices, but in both directions, and that we should be able to reconstruct the transform images in a storage type convolver made on the same two dimensional principle. We would expect, as the work proceeds, to test such two dimensional storage type convolvers, which should have, eventually, storage capacities of as much as 10^5 bits per square cm.

II. PRESENT STATUS

A. Airgap Devices

1. Introduction

In the last report, we discussed some of the problems of the ZnO on Si devices and indicated that we felt that it would be worthwhile to pursue a program of improvement on the airgap devices, so as to prove some of the principles of the optical imaging device that we have been pursuing. Because the work at Lincoln Laboratories indicated that it is, indeed, possible to make mechanically stable airgap devices, we felt that it was important to take advantage of this type of technology. Therefore, we are following two parallel programs: one on an airgap device; the other with the ZnO on Si technology.

In the last progress report, we proposed to construct a mechanically stable airgap device with p-n junctions laid down into the Si, so that the interaction with the Si occurred within the depletion layer of the p-n junctions, rather than at the surface. This is to eliminate surface state problems and to make the storage time of generated holes within the device more controllable. Most importantly, this change in the technology would make it possible to eliminate the diffusion of generated carriers parallel to the surface of the semiconductor, because of the potential barrier associated with junctions, and so cause the modulation transfer factor, MTF, to remain essentially constant with spatial frequency.

As far as the system aspects of this device are concerned, we have used, as described in the last progress report, an optical grating in the path of the light beam to introduce periodicity into the light beam. By this means, we were able to work with two widely separated input frequencies

and make a device with a large dynamic range; one in which the dark current is relatively small, because the normal convolver output occurs most strongly when the two input frequencies are equal. A device of this kind is somewhat more difficult to make because there is some loss of light intensity, due to the presence of the grating, and it is difficult to test it as a convolver in normal operation, because of the widely different input frequencies and, in fact, the lack of dark current. We, therefore, decided to carry out our initial tests on the new device which we have constructed using a somewhat different mode of operation; one which should be of importance, eventually, to infrared detection.

In this device, we are using broadband input transducers with identical characteristics, but with a center frequency of 100 MHz, and a bandwidth of 35 MHz. By using the two input chirp signals in the manner which we have described previously, we obtain an output which is the spatial Fourier transform of one line of the optical image. We then employ a dispersive delay line system, to be described later, to take the inverse Fourier transform of the output signal, and thus reconstruct the image. In the Fourier transform plane, frequency corresponds to distance along the line, so that eliminating certain frequencies eliminates certain parts of the picture. On the other hand, time in the Fourier transform output, time corresponds to the spatial frequency in the image. Background illumination, or output in the dark, corresponds to a signal with a zero, or at least a low, spatial frequency. In the Fourier transform plane, this corresponds to the signal output from the device at a certain time T. By gating the output of the device, these spatial frequency components around the time T are eliminated. Thus, by taking the inverse Fourier transform, we can eliminate the dark current or, more

importantly, we can eliminate much of the background illumination component.

We have now constructed silicon convolvers of the type described, using arrays of p-n junctions, which have yielded convolvers with good efficiency. The mechanical problems have been solved by supporting the silicon 1500 Å away from the $LiNbO_3$ substrate by means of rails 4 μm wide along the direction of propagation. These rails are obtained by removing the $LiNbO_3$ between them by rf sputter etching. The experiments show that the mechanical loading due to the contact at the top of the rails and silicon slab is negligible. The configuration employed is far simpler than that using small posts, the masks aremuch easier to make, and the rf etching technique is very easy to employ. The experimental results which have been obtained prove the principles of Fourier transform signal processing of the image, and show unique features not existing in CCD devices.

2. Experimental Results

The general configuration used for the convolver is shown in Fig. 1. The 3 finger pair transducers are centered at 100 MHz; the acoustic beam width is 1 mm and the silicon slab is 2 dm long. Fig. 2(a) illustrates the conventional airgap configuration in which sputtered SiO_2 rails support the silicon slab. This has the disadvantage that the silicon between the rails bends easily under a slight pressure, so it is difficult to maintain a uniform airgap, and contact can be easily made with the delay line in the region where the beam propagates. Fig. 2(b) illustrates a configuration in which the silicon is supported by 4 μm x 4 μm posts, which are obtained by ion beam etching. In this technique used by Lincoln Laboratories, the posts are randomly placed to avoid coherent reflections. A pattern generator is necessary for making the mask used for the photolithography, and the inspection of the final pattern for imperfections

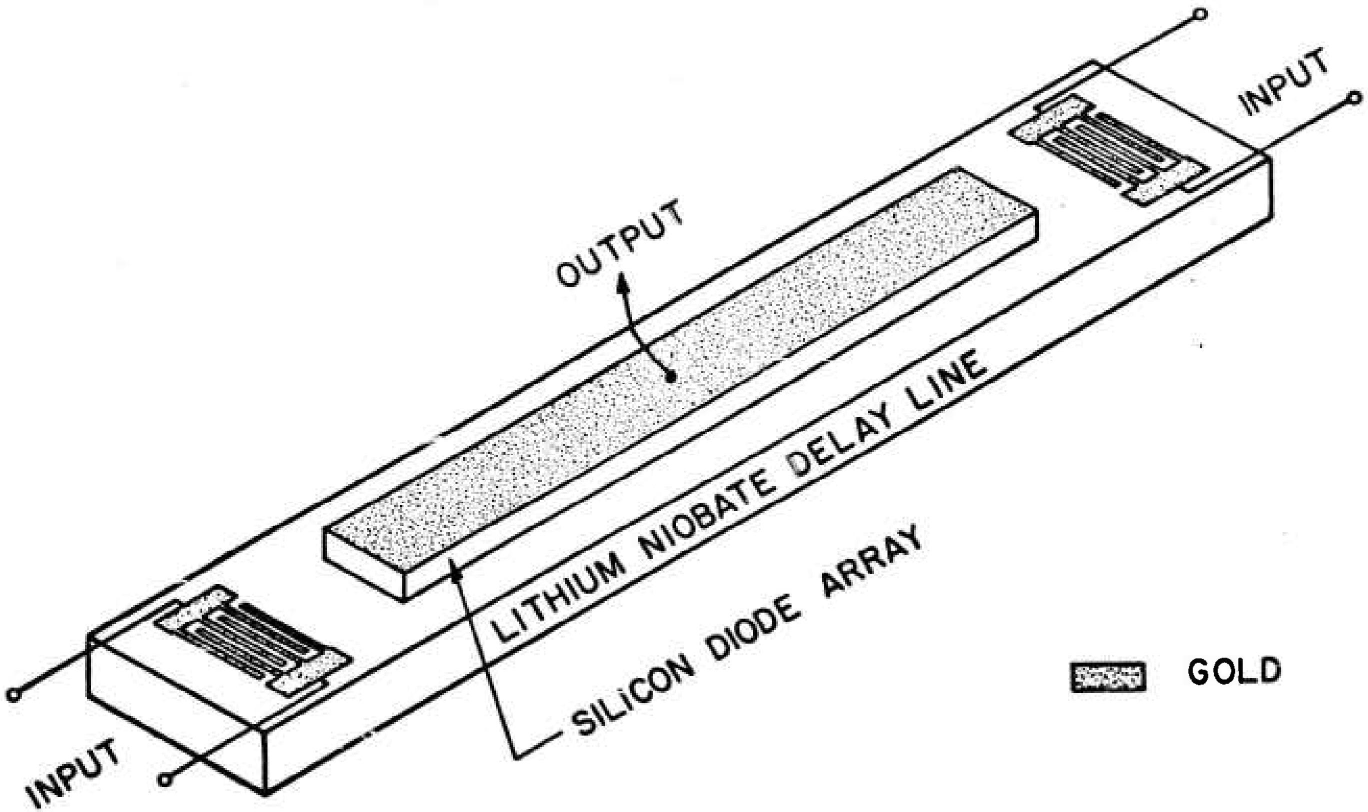


FIG. 1--General configuration.

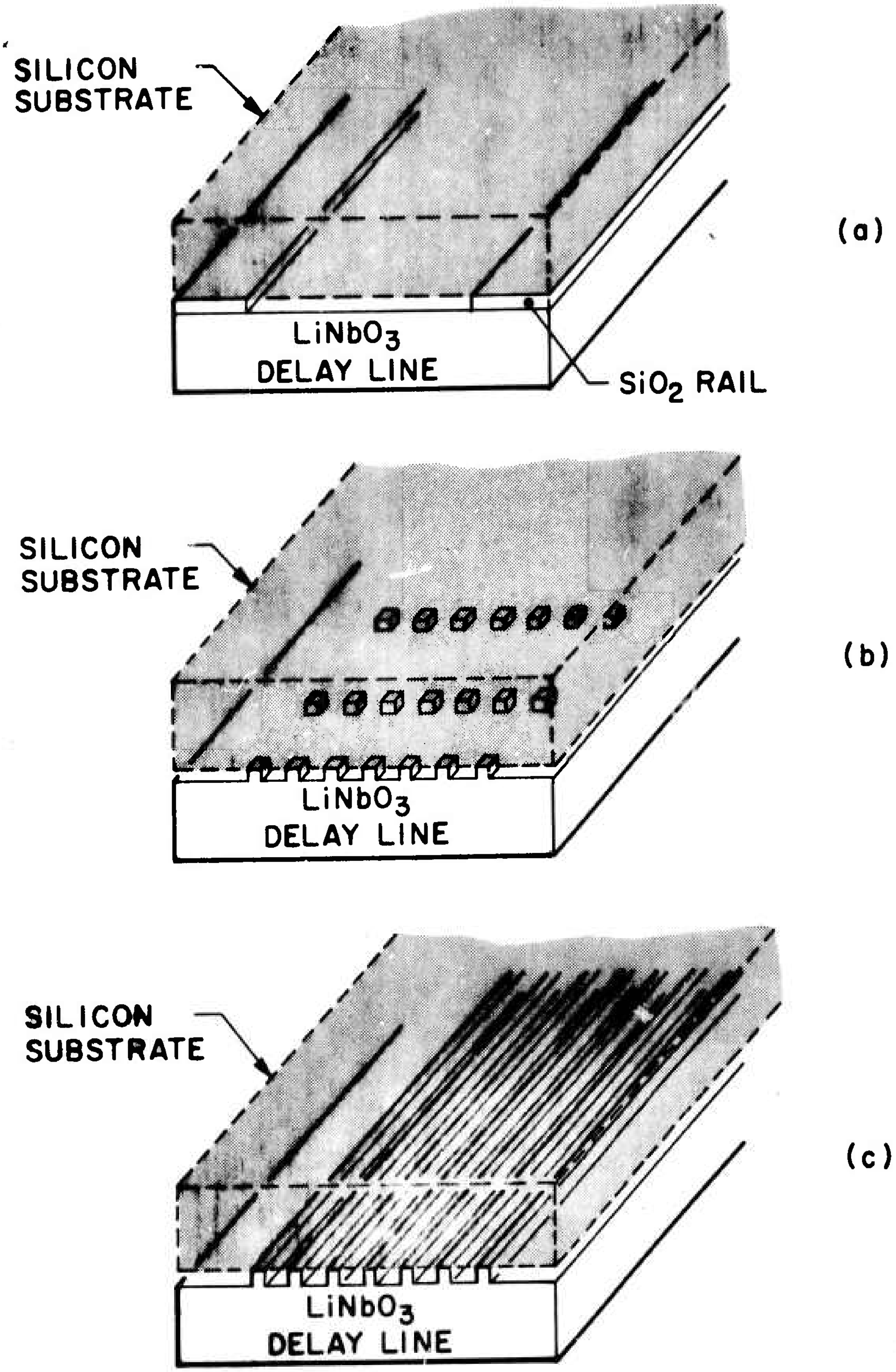


FIG. 2--**Air Gap Convolver:** (a) configuration with SiO_2 rails; (b) configuration with posts (MIT); (c) configuration with narrow rails.

is extremely tedious. If one post is missing, there is a risk that the silicon will make contact with the delay line in the vicinity of the missing post. Fig. 2(c) shows the rail configuration which we are using. The 4 μ wide rails with 150 μ spacing are obtained by rf sputter etching. The mask is not very difficult to make and does not require the use of a pattern generator. The final pattern inspection is simple and there is no risk of coherent reflection from the rails, since there is no longitudinal periodicity. There is some question as to the amount of loading due to the contact between the silicon and the top of the rails, but, because the total rail area is very small compared to that of the acoustic beam; this effect, as we expected, is negligible in our experiments.

Fig. 3 shows how the different parts of the rail system fit together. The 20 mil thick sapphire substrate is essentially used as a mechanical support; the semitransparent gold was used to provide the ground continuity underneath the delay line. However, we found that we can remove this thin gold under the acoustic beam without changing the characteristics of the convolver. This seemingly minor modification turns out to be an important one, since it allows the control of the uniformity of the airgap by inspection through the transparent sapphire of the interference pattern between the silicon and the delay line. If the gap is uniform, we see a uniform gray area over the 2 cm long interaction region. This is desirable not only because of mechanical consideration, but also because it implies that, with this configuration, light enters the silicon with very little reflection. The silicone rubber block assures the right location of the output contact and silicon slab, while distributing the pressure evenly over the silicon. One of the major advantages of this

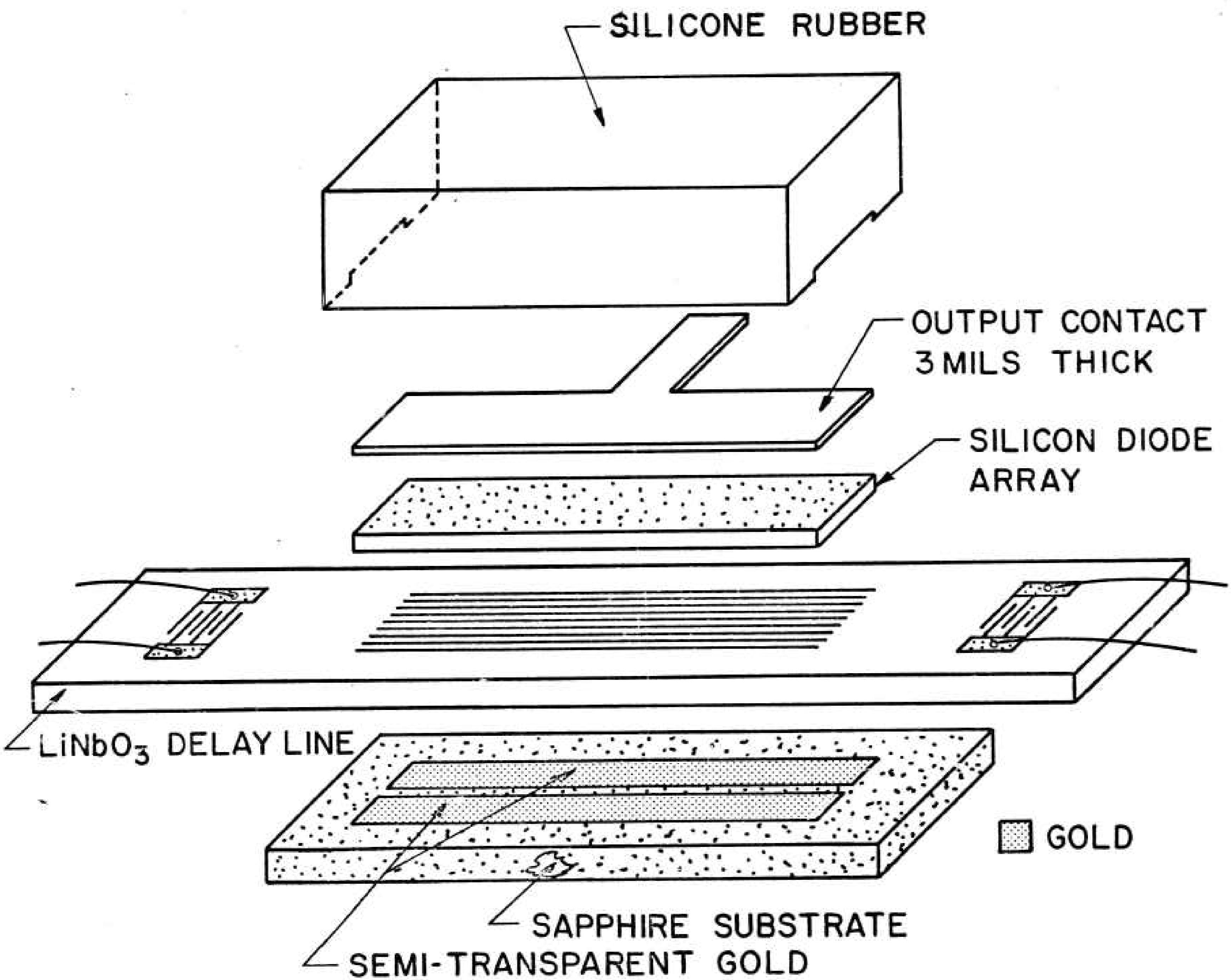


FIG. 3--Convolver exploded view.

configuration is that the silicon slab has no leads soldered to it, there is only a pressure contact between the silicon and a beryllium copper sheet. This implies that the silicon can be handled and cleaned in sulfuric acid just before assembly; thus the dust problem is considerably eased.

Until now, we have been using unspecified silicon as far as the surface finish is concerned. If the surface is wavy as a result of chemical polishing, it is necessary to apply a fairly high pressure in order to eliminate these waves and obtain a uniform gap. If the periodicity is too small or the valleys too deep, the gap cannot be made uniform. Fortunately several areas of a 2" diameter silicon wafer are sufficiently flat and, thus, at least five out of the fifteen diode arrays processed simultaneously on the wafer are usable. The best solution to this problem would be to use exclusively mechanically polished wafers.

In Fig. 4 we show the effect of mass loading with 1100 Å high rails. The curves labeled "substrate held by wires" and "substrate in package" correspond to the unloaded delay line; the difference between them is due partly to the measurement accuracy (± .25 dB) and partly to the difference in the stray capacitances of the transducers to ground. For all these experiments, the input matching networks were kept unchanged. The mass loading experiment was carried out by using a low-loss slab, such as .01 Ω-cm silicon or glass, instead of the p-n diode array normally used; such materials should contribute negligible electrical loss. The loading observed in this experiment was initially disappointing, but it was realized later that it is due to the contact between the slab and the delay line occurring in the region between the rails because of excessive applied pressure. This first experiment is not entirely negative, since

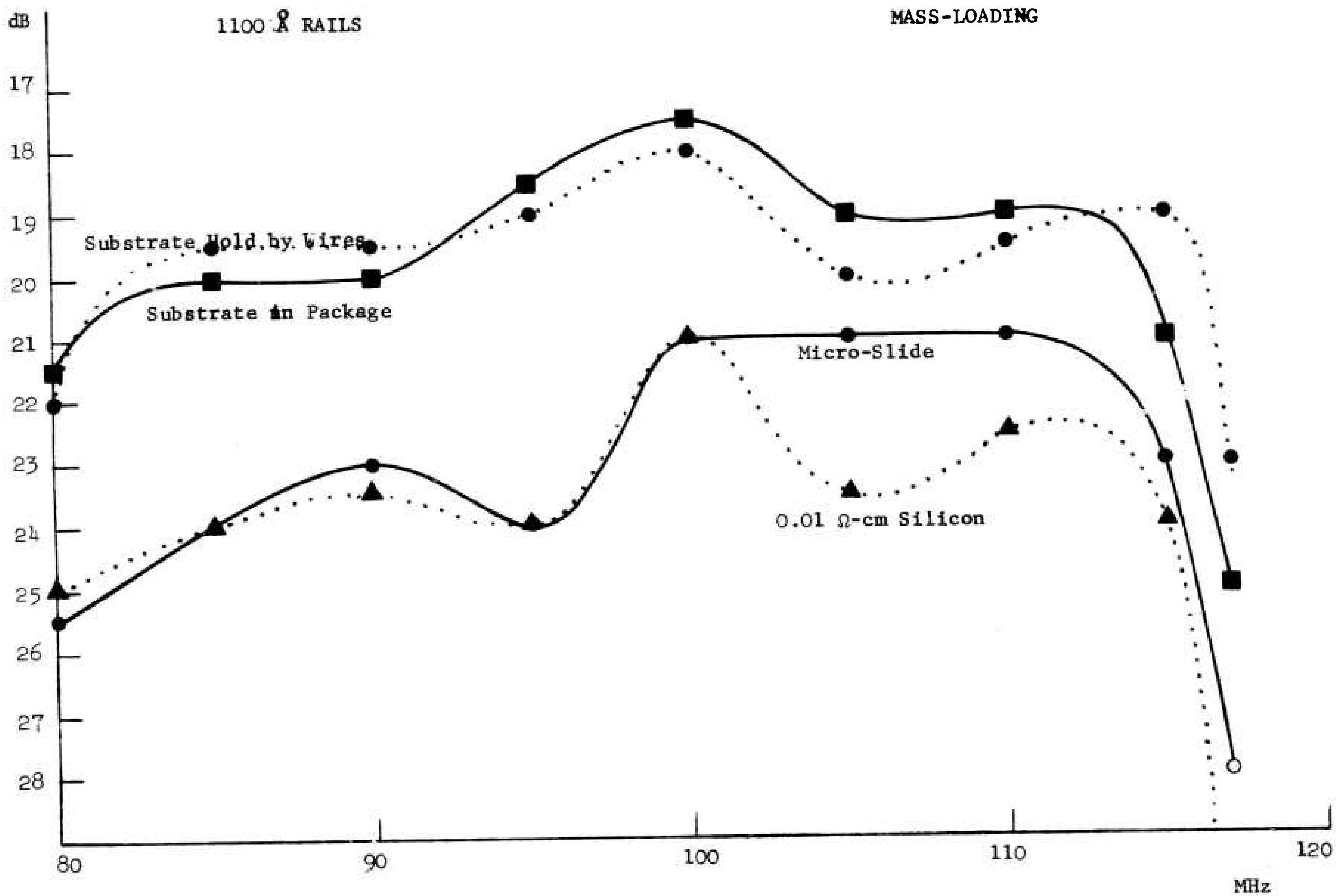


FIG. 4--Insertion + transmission loss.

it allowed us to get a feel about the deformation of the silicon slab under uniform pressure and how to relate the yield of the silicone rubber to the applied pressure.

Fig. 5 shows the mass loading with 1300 Å thick rails. The results obtained are much better in this case; but here too we realized later that the slabs were still touching the delay line in a few spots. The results in Fig. 6 correspond to 1500 Å rails. The curve labeled ".01 Ω-cm silicon - extra pressure" is associated with a pressure even higher than in the two preceding cases (about 5 to 10 pounds over an area 2 cm x 2 mm). The two other curves corresponding to reasonable pressures are essential identical, if we take account, as already mentioned, of the measurement accuracy and the difference between the stray capacitances of the transducers. It is seen that with the 1500 Å thick rails, the mass loading effect is essentially negligible.

The transducer matching network is shown in Fig. 7. The values of the inductances and capacitances have been optimized numerically with a computer program developed at Hewlett Packard. The philosophy of design is much the same as that for the ZnO on Si transducers described in the last Progress Report, except that now the problem is to match from a 50 Ω line into a relatively high impedance of 200 ohms. The constraint is that the response of the transducer between 80 and 120 MHz be as flat as possible, allowing 2 dB of mismatch loss. Figures 8 and 9 show the theoretical response of a transducer and the input impedance of the matching network. The overall transducer to transducer response involves extra losses due to the two way directivity of the transducers, and to the diffraction losses of the acoustic beam on the surface of the delay line. The experimental broadband matched response is shown in Fig. 10. The narrow

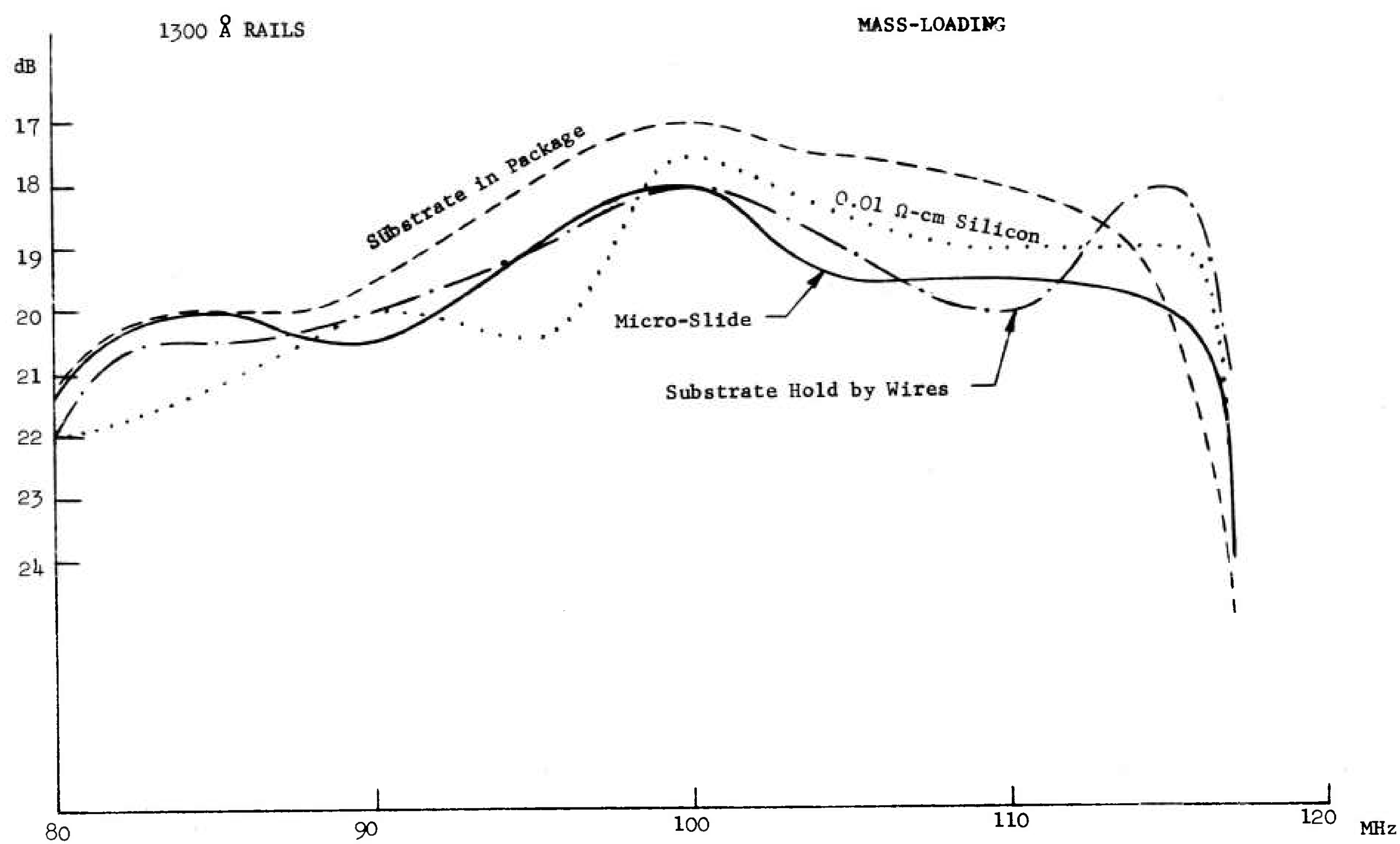


FIG. 5--Insertion + Transmission Loss.

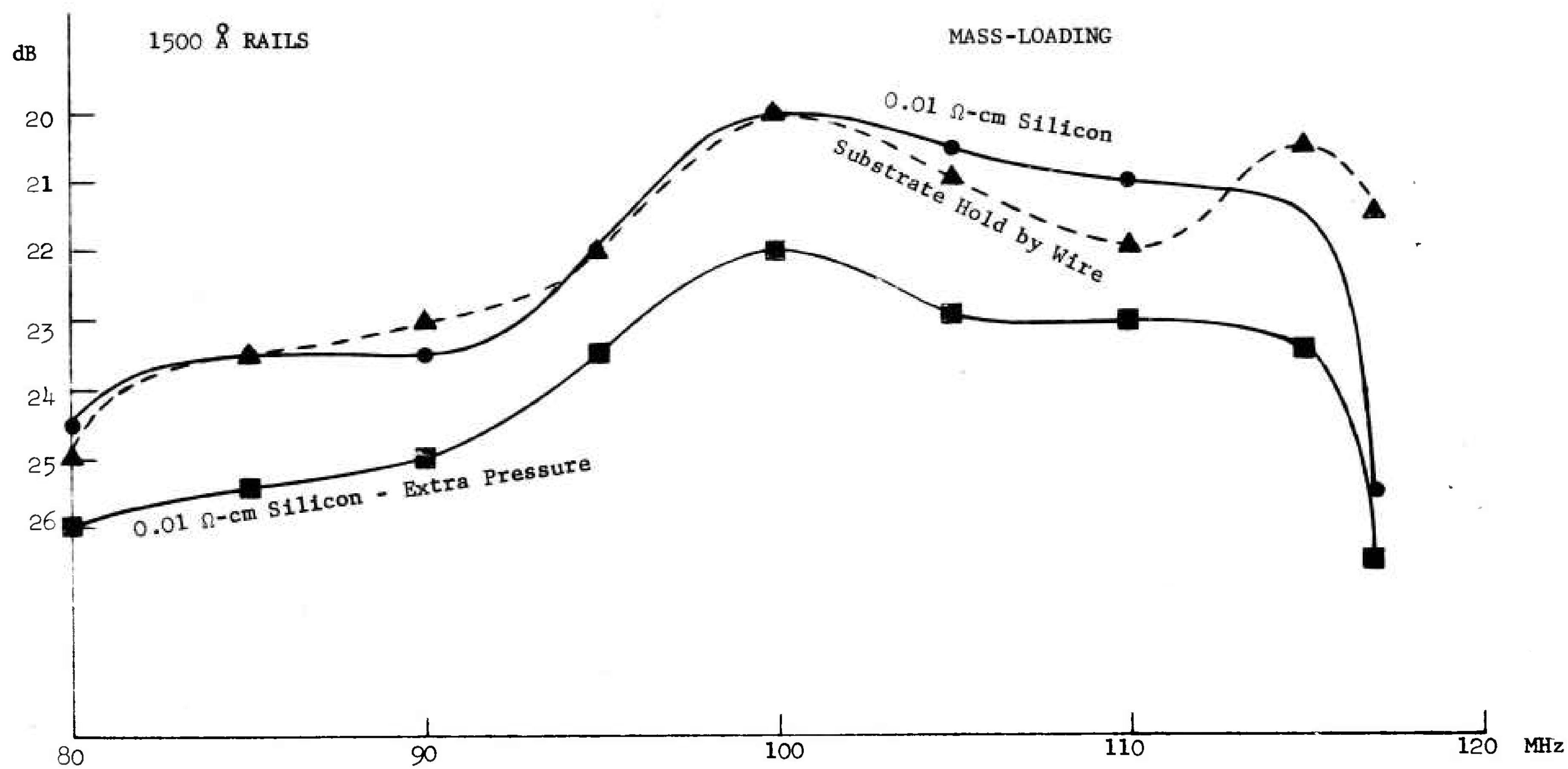
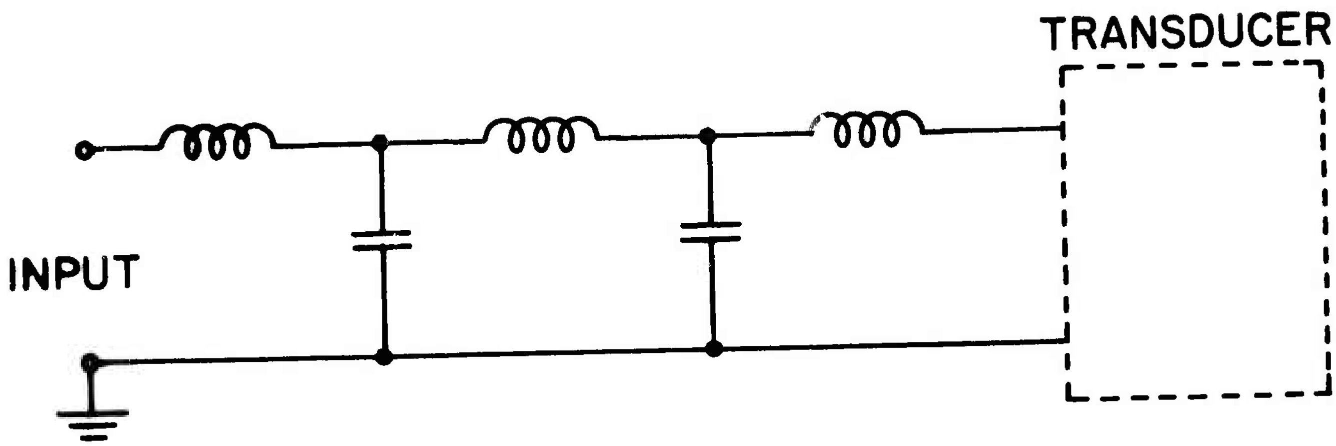


FIG. 6--Insertion + transmission loss.



TRANSDUCER MATCHING NETWORK

FIGURE 7

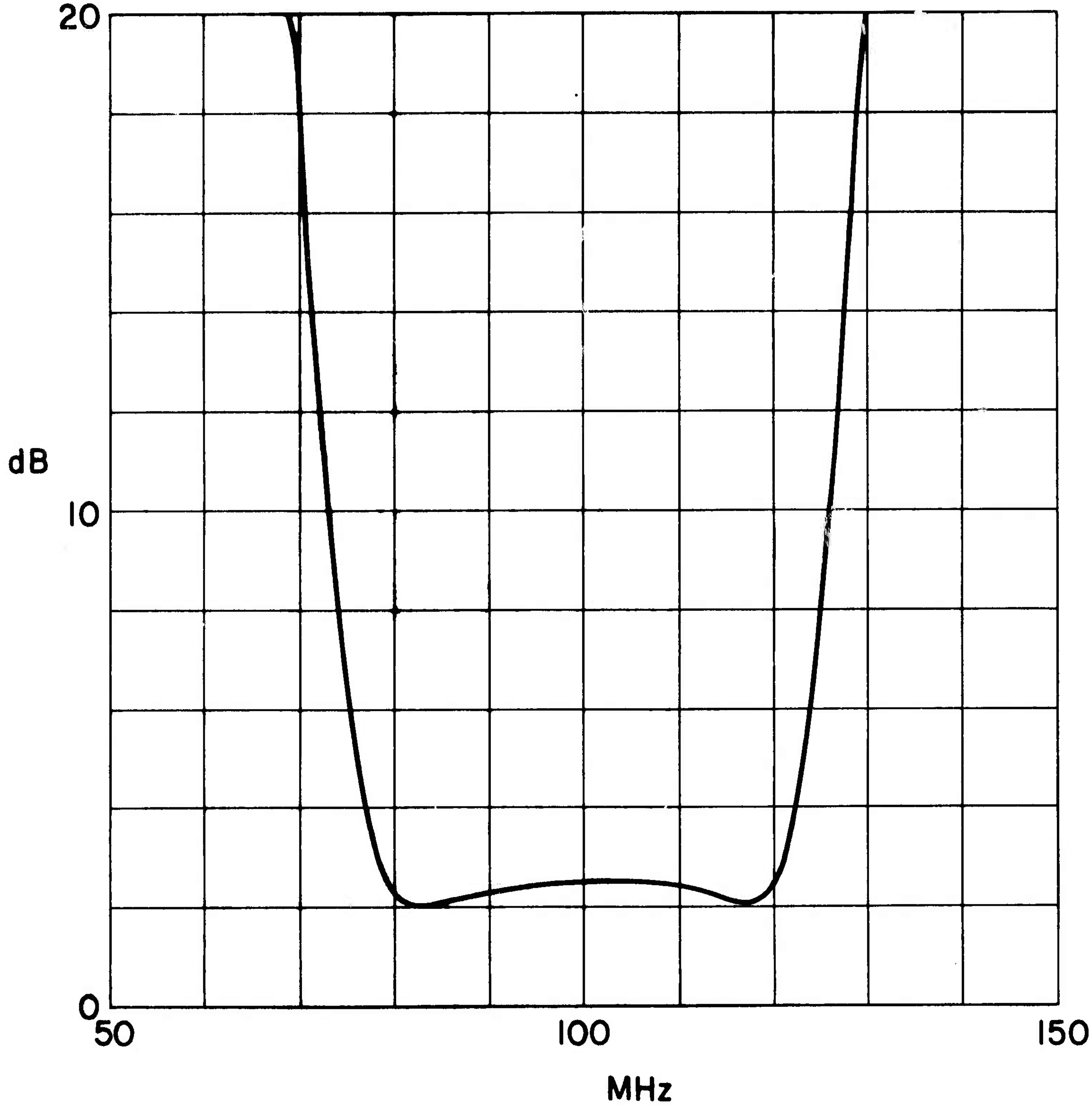


FIG. 8--Transducer response.

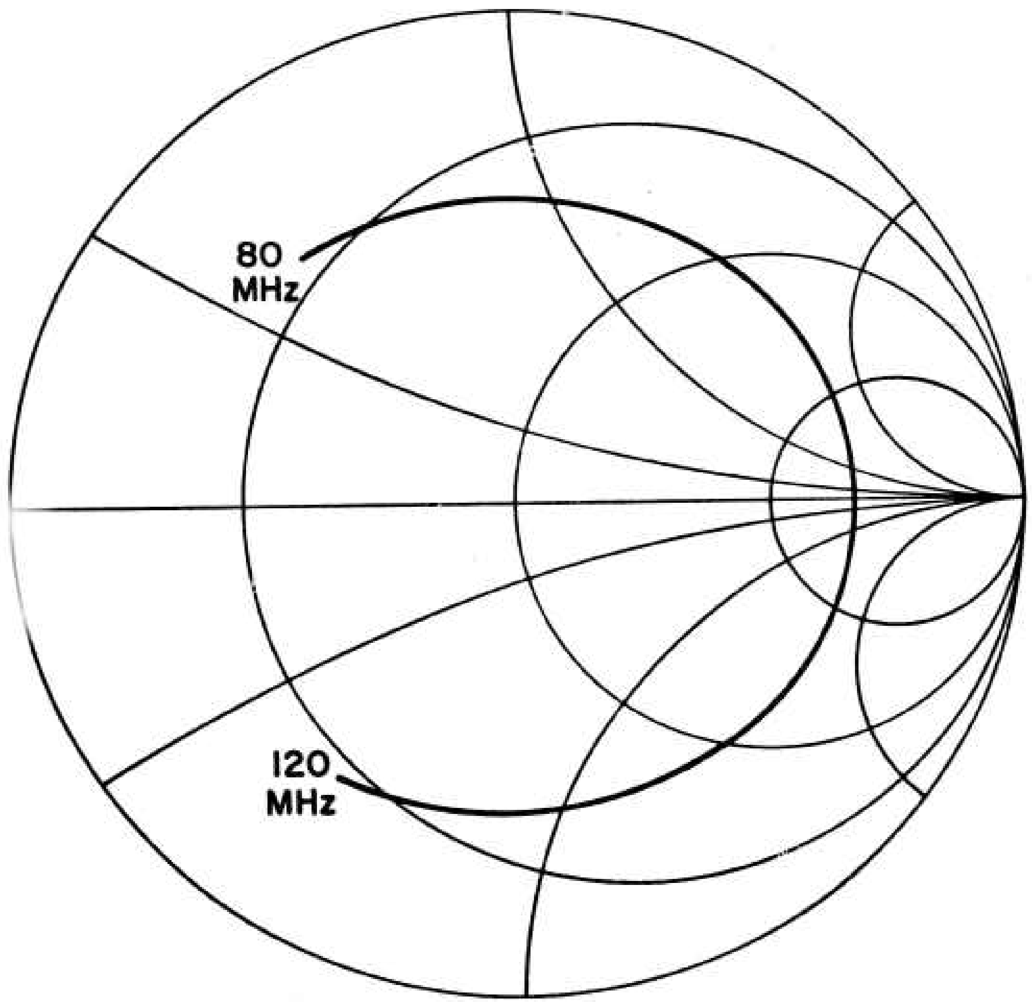


FIG. 9--Convolver input impedance.

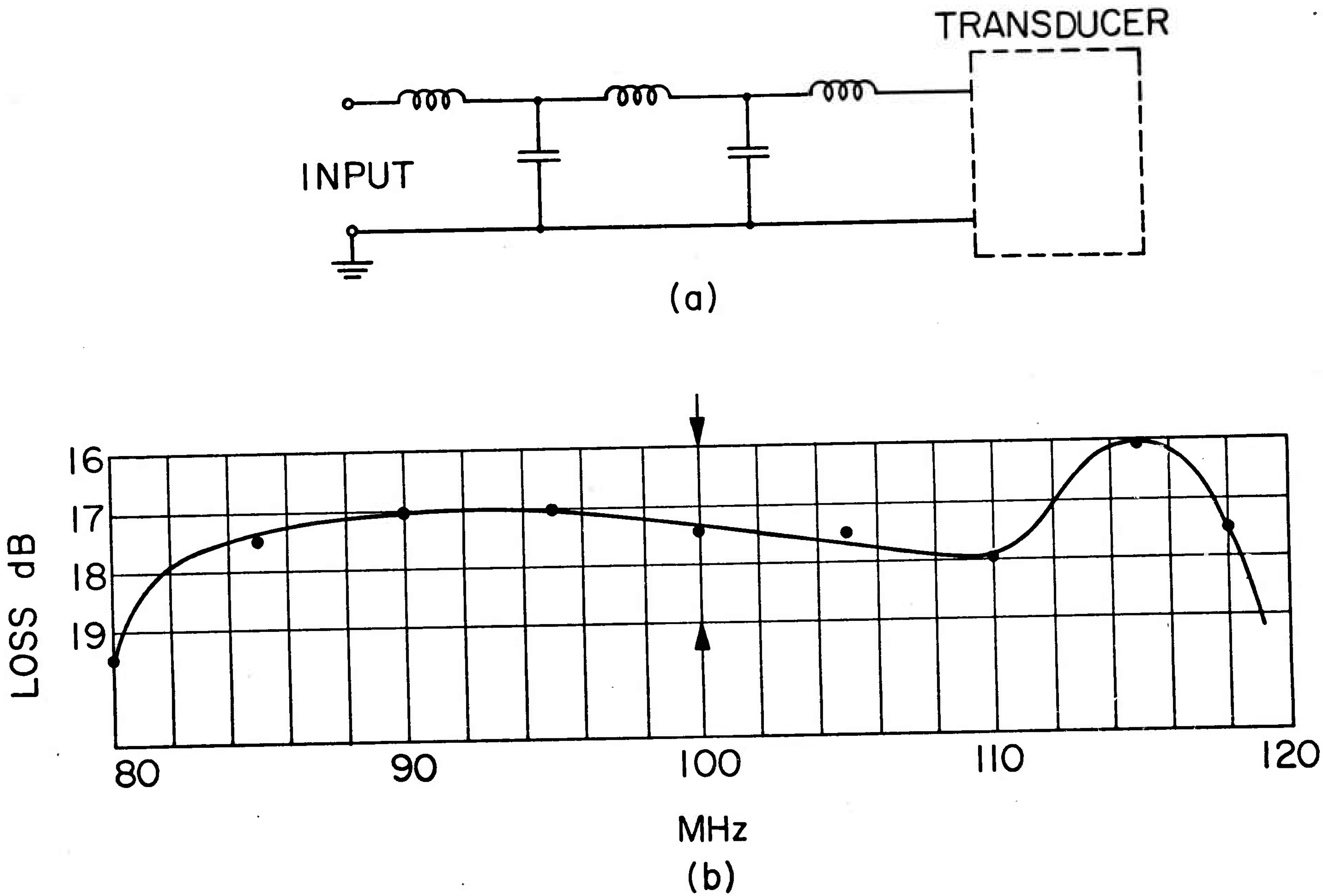
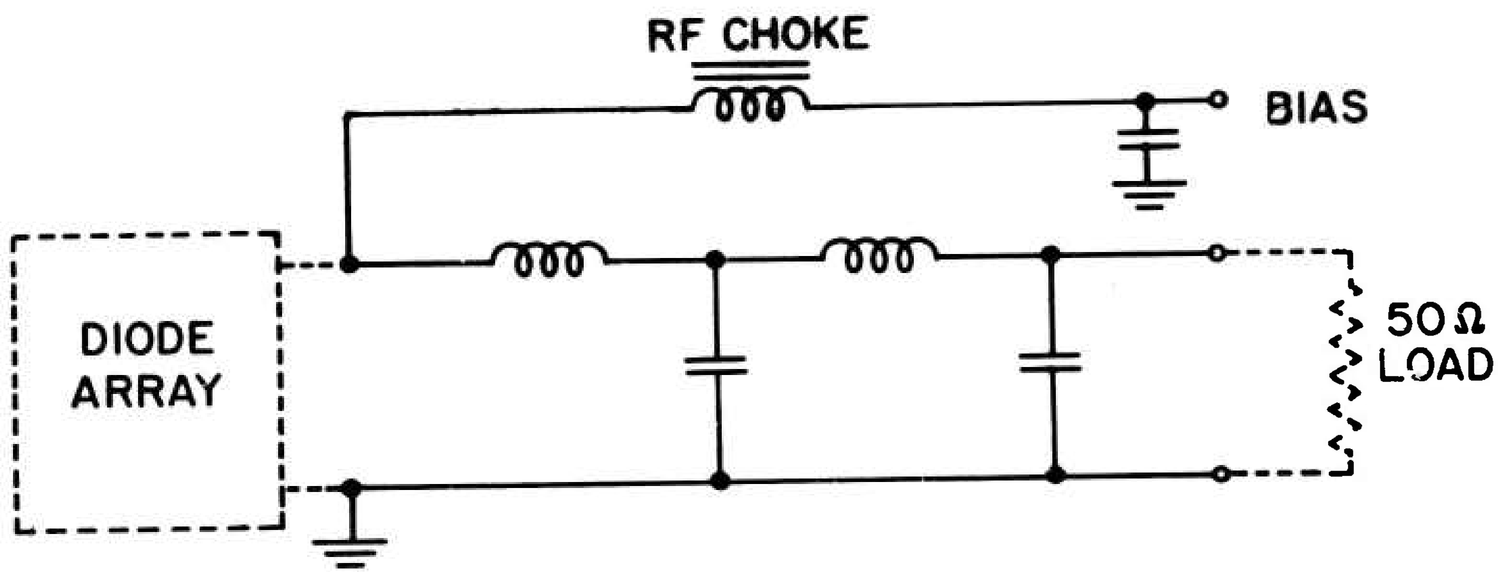


FIG.10--Insertion + transmission loss (18.5 dB @ 100 MHz).

band insertion loss with matched inputs if 13 dB, while the broadband terminal to terminal loss is 18.5 dB over a 38% bandwidth.

The output matching network of Fig. 11 is primarily used when the frequency range of the output signal is not too wide. The matching network i 'ig. 12 has a wider bandwidth ($\approx$ 60 MHz) and has to be used, for example, when feeding short pulses into the transducers. The two 50 Ω coaxial cables in parallel form an equivalent 25 Ω line, which is a quarter wavelength long at the central frequency (200 MHz). The inductance tunes out the convolver output capcitor, which is of the order of 30 pf.

We have constructed all these airgap devices with arrays of p-n junctions or Schottky barriers laid down on an n-type semiconductor substrate. The purpose is twofold: 1) to remove the interaction region from the surface of the semiconductor so as to eliminate surface state problems and obtain more consistent results. Here the interaction is in the depletion layer of the p-n junction or Schottky barrier diode; 2) to trap generated carriers in the region of the junction. Because of the potential barrier set up around the depletion layer, holes generated in this region cannot move out into the surrounding n region, and hence cannot diffuse parallel to the semiconductor surface. The MTF of the system, therefore, tends to remain uniform out to the highest spatial frequencies required. Our experiments described below have mainly been carried out with arrays of p-n junction diodes. However, in the airgap devices we have also made some experiments with Schottky barrier diodes and have observed storage of up to 100 msec. We have only obtained relatively poor light sensitivity in these diodes, because the poor transparency of the PtSi, and because theoretically, as discussed in Sec. A3, we would not expect as good a light sensitivity as with a p-n junction diode. This is because the voltage



OUTPUT MATCHING NETWORK

FIGURE 11

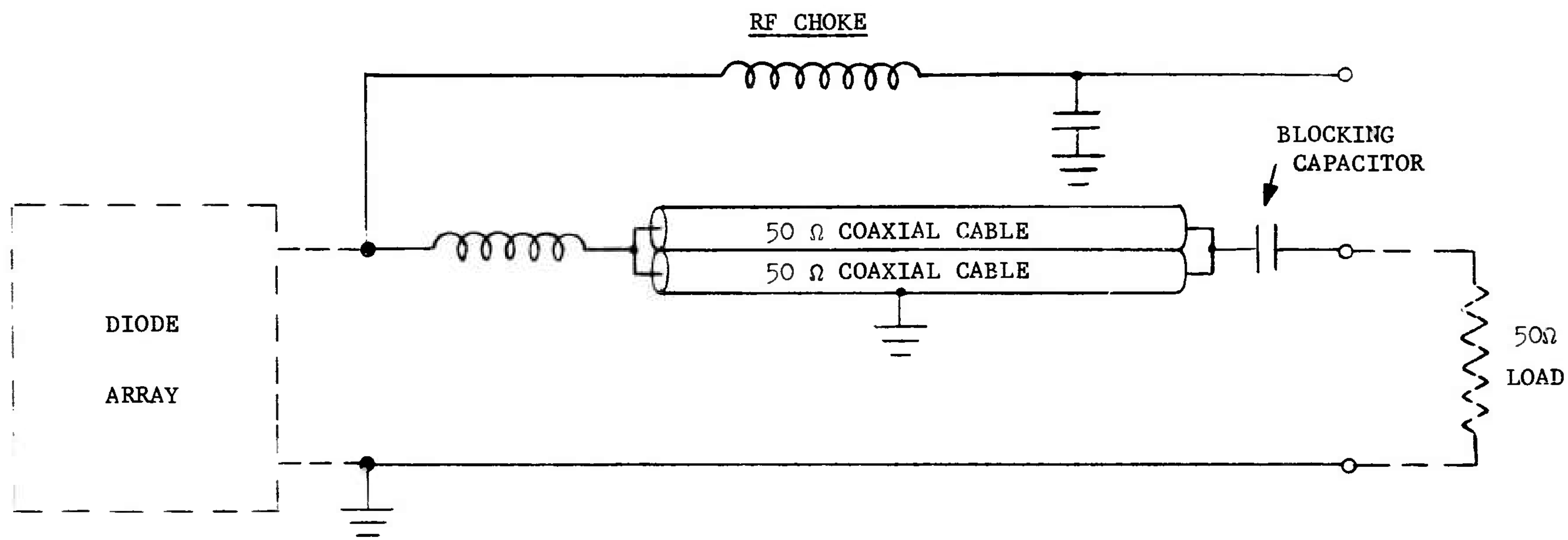


FIG. 12--Output matching network.

change required to obtain a given forward current across these diodes is less than that for p-n junction diodes. As the convolver can be regarded as a photovoltaic device, this implies that the p-n junction device is more light sensitive.

Fig. 13 shows four different diode array patterns. In order to minimize the reflections from the diodes, we chose 8 μm and 24 μm periodicities, corresponding to $\lambda/4$ and $3\lambda/4$ respectively, where $\lambda = 32\ \mu$ is the acoustic wavelength at 100 MHz central frequency. If we consider a propagating wave at 100 MHz, then the reflected wave from any diode is cancelled by the wave reflected by the following diode, since the extra path length involved is $\lambda/2$ or $3\lambda/2$. The wide diode patterns (24 μ periodicity) were chosen in order to maximize the diode area. The reason behind the choice of the segmented diodes is two fold: first, if a segment is not good, or if two segments are inadvertently linked, the corresponding row or rows still have 8 out of 9 good diodes; secondly, if the silicon slab is not perfectly parallel to the acoustic beam as shown in Fig. 14, then the points A and B are not subjected to the same electric field, and current might flow between these points, providing some extra losses. It is also apparent that the effective width of the diode should be small compared to the wavelength to avoid problems with angular misalignment; in this case, the reflection coefficient will also be smaller and not vary as rapidly with frequency. Thus, the narrow diodes should be better than the wide ones and the segmented ones better than the straight ones. The experiments confirm this point.

The diodes are of the p^+-n type obtained by boron diffusion into n-type silicon. The junction depth is approximately $\frac{1}{2}$ μm and the sheet resistivity of the p^+ region is of the order of 100 $\Omega/\square$. We investigated

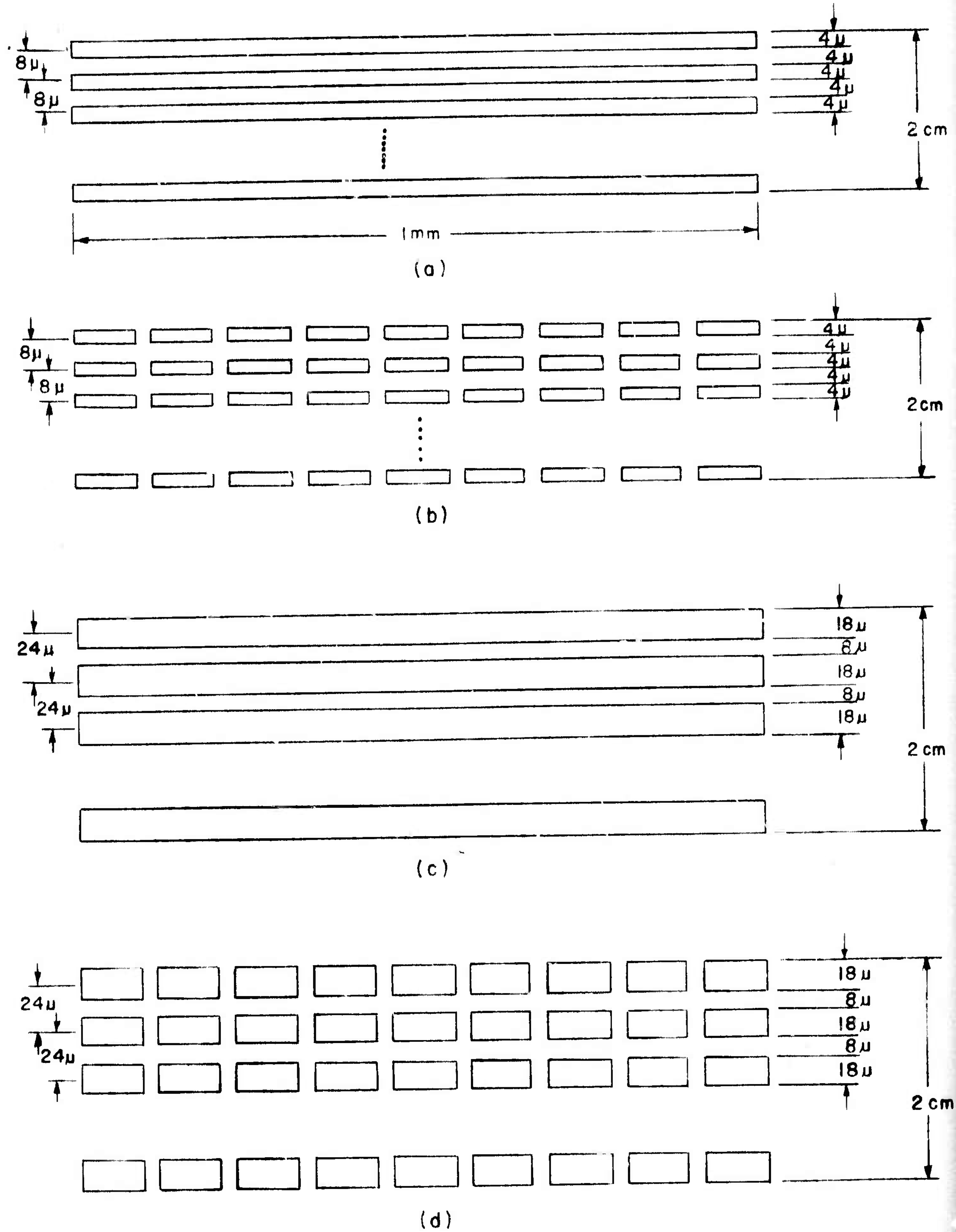


FIG. 13--Diode array patterns.

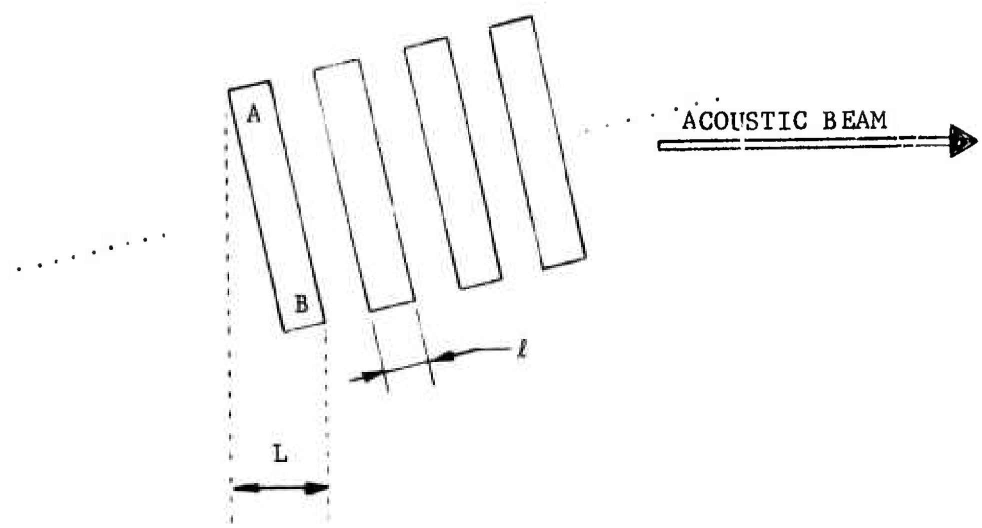


FIG. 14--Diode array misalignment.

three types of n-type substrates: bulk silicon 5-15 Ω-cm; 15 Ω-cm epi, 10 μ thick on n^{++} material; 50 Ω-cm epi, 10 μ thick on n^{++}. In our first experiments, the diodes were protected by a 1000 Å thick SiO_2 layer; on later experiments we etched away the oxide. Some of the results we obtained with both the oxidized and stripped surfaces are shown in Figs. 15 to 21. These are representative of a large number of experiments, too numerous to describe here.

In general we found, as we would expect from the theory, that the diodes made of high resistivity material (≈ 50 Ω-cm) yield the best convolution efficiency, and consequently saturate at lower levels than the diodes made of lower resistivity material in the 5-15 Ω-cm range. The high resistivity diodes were also more light sensitive than the low resistivity diodes. We describe here mainly the results on the 15 Ω-cm material, because, in general, this material can be made with better uniformity and reproducibility than the higher resistivity material, so that, in the long run, this material or an even lower resistivity material would be the correct one to choose for the optimum design of an optical imaging device or acoustic convolver. The results obtained for narrow segmented dioes using 15 Ω-cm, 10 μm thick epitaxial material on an n^+ substrate with 1000 Å layer of SiO_2 are shown in Fig. 15. It will be seen that the convolution efficiency is - 62 dBm, with a very slight tendency to saturation with equal input powers near 20 dBm. This result should be compared with the results obtained in this laboratory by Gautier on the best airgap convolvers under narrow band condition which only had an insertion loss of 11 dB and an efficiency of -42 dBm.[2] In this case, with an insertion loss of 18.5 dB, and the p-n junctions only filling approximately half the area of the semiconductor, we would expect a loss of convolution efficiency

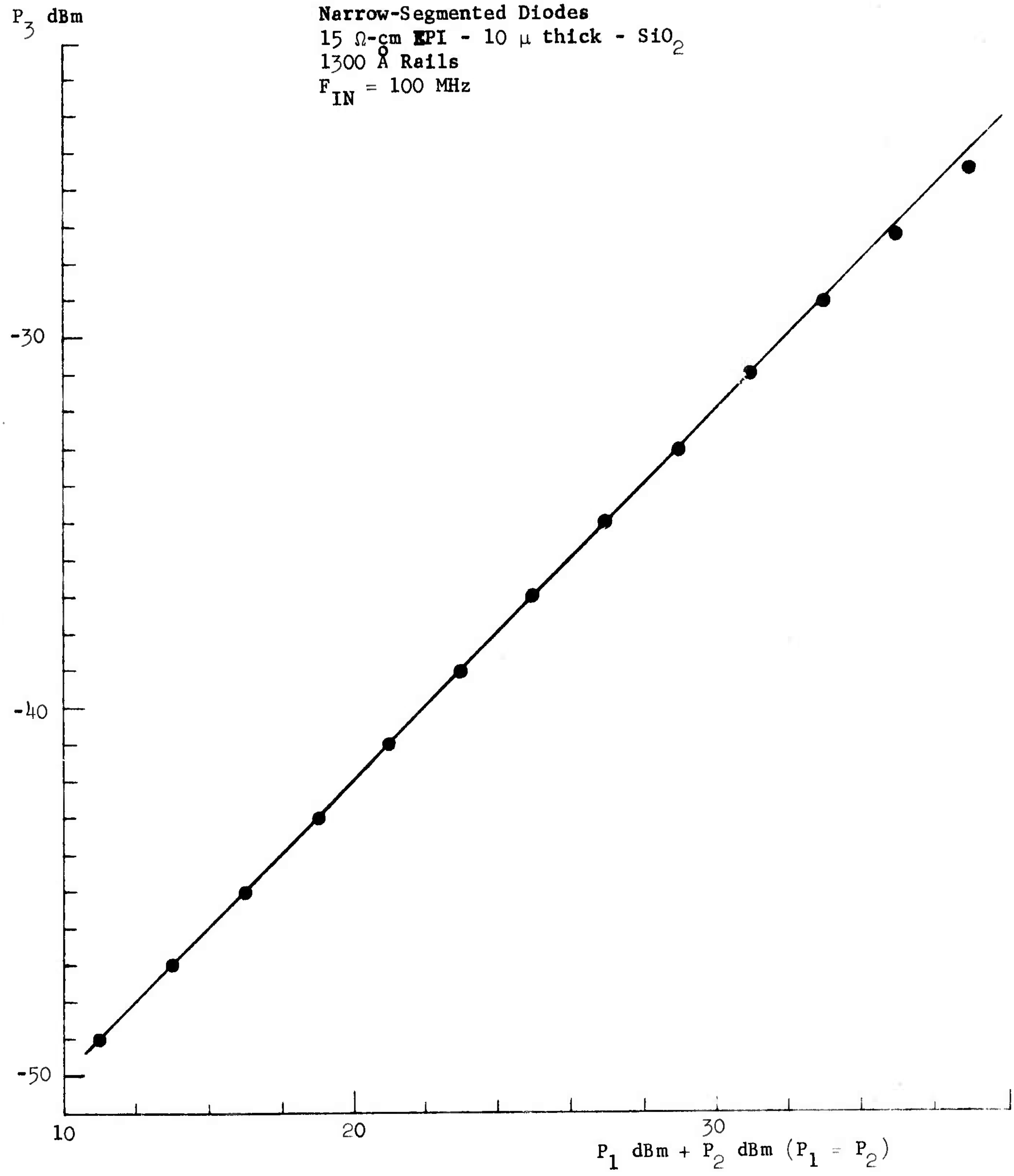


FIG. 15--Output power versus input power.

of the order of - 11.5 dB at best. In fact, with the higher resistivity material, the optimum efficiency measured was of the order of approximately - 56 dBm, so the results compare very favorably to those of the best airgap convolvers, with the additional advantage that much greater reliability in the mechanical construction of the device.

A second set of measurements were taken using the same material and configuration with the surface stripped of oxide. Typically, this implies that approximately 50 Å of oxide is present and that, under such conditions, an n-type silicon surface is depleted. These, in fact, were the conditions under which uniform airgap convolvers are operated most efficiently and which are used both at Lincoln Laboratories and in this laboratory. In this case, normally it is expected that the surface is very little influenced by external fields, because typically there are a very large number of surface states present. This is in contrast to the situation when a layer of oxide is thermally grown on the surface. In this case, an n-type layer is typically accumulated. As will be seen from Fig. 16, the measured low level conversion efficiency was now changed to - 56 dBm. We believe that there are two causes for this effect. The first is that now, as the surface between the junctions is depleted, the junction width itself becomes larger, so that the junctions effectively occupy a larger proportion of the total area of the semiconductor. In addition, we might expect that, even in the presence of a large number of surface states, the junction itself would be more affected by the presence of external fields, because it only takes a relatively small change in potential at the surface in the depletion region to change the width of the junction. This certainly appears to be the case in our experiments. An additional reason

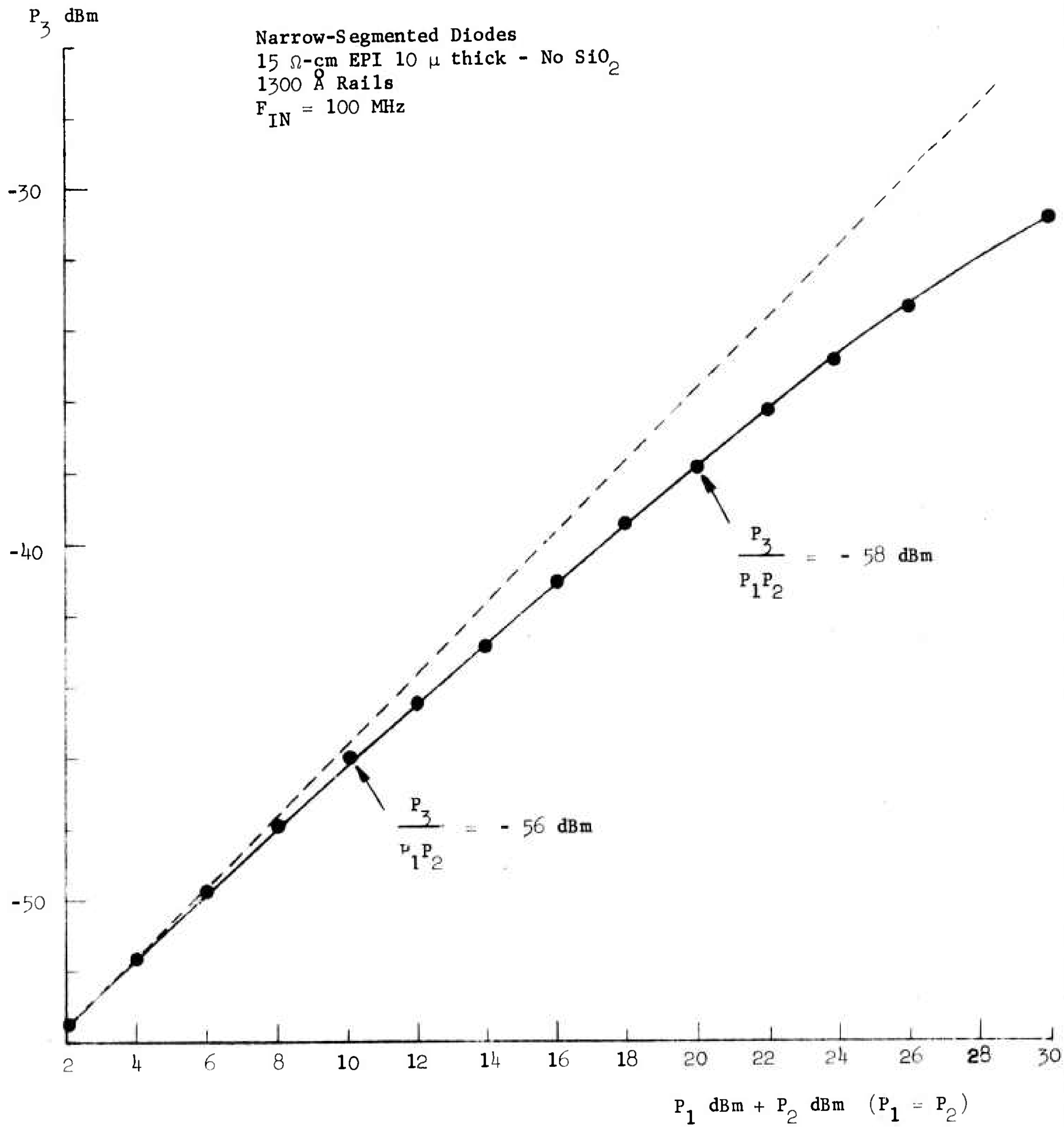
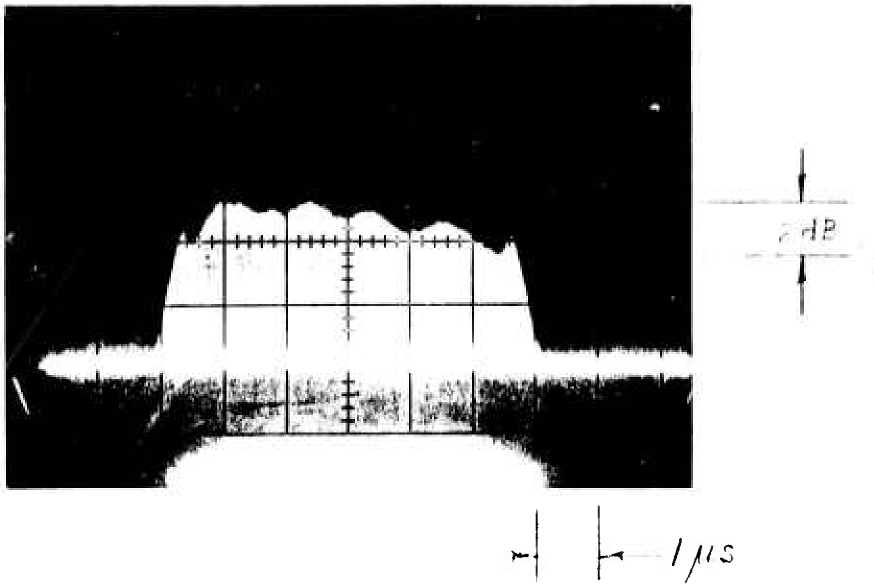


FIG. 16--Output power versus input power.

for the improvement in sensitivity is, of course, that the outside layer has been stripped. The semiconductor surface is now 1000 Å nearer the surface of the $LiNbO_3$, so that there is a slight increase in the coupling between the surface wave and the semiconductor. However, it should be pointed out that, in all cases, one would expect the potential across the p^+n layer to be considerably larger than the potential between the depleted surface and the bulk region, due to the heavy doping of the p^+ region. Therefore, when illuminated with light, holes that are generated in the depletion layer will still not be able to pass from one junction to a neighboring one. One other point should be made, this is, as will be seen from Fig. 16, that when the convolution efficiency is increased by 6 dB, the input power where saturation begins decreases by a considerably larger quantity, of the order of 15 dBm.

Measurements of the uniformity of the interaction regions are shown in Figs. 17, 18, and 19. These are carried out by inserting a short pulse at one end of the convolver and a long pulse at the other and measuring the output. The nonuniformity is due to two reasons; 1) the variation in the airgap; 2) small reflections from the junctions. It can be seen that the stripped surfaces give slightly better uniformity and, somewhat surprisingly, the wide segmented diodes are a little more uniform than the narrow ones. However, their efficiency is worse by 4 dBm than the narrow segmented diodes. Later experiments with 5 Ω-cm material, which are not shown here, indicate still better uniformity than are given by these results, with some dropoff in efficiency. We believe that this is because the discontinuity at the p-n junctions is decreased with lower resisitivity material.

The response to light of a convolver of this type is shown in Fig. 20.



$P_1 = P_2 = 16$ dBm

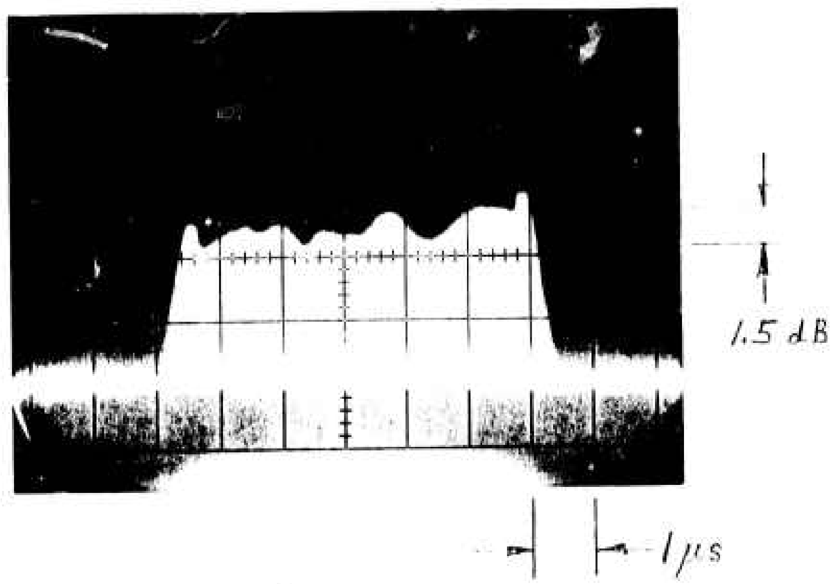
Narrow-segmented diodes

15 Ω-cm EPI 10 μ thick - SiO_2

1100 Å Rails

Efficiency: -61.5 dBm @ 100 MHz

FIG. 17--Interaction region uniformity.



$P_1 = P_2 = 16$ dBm

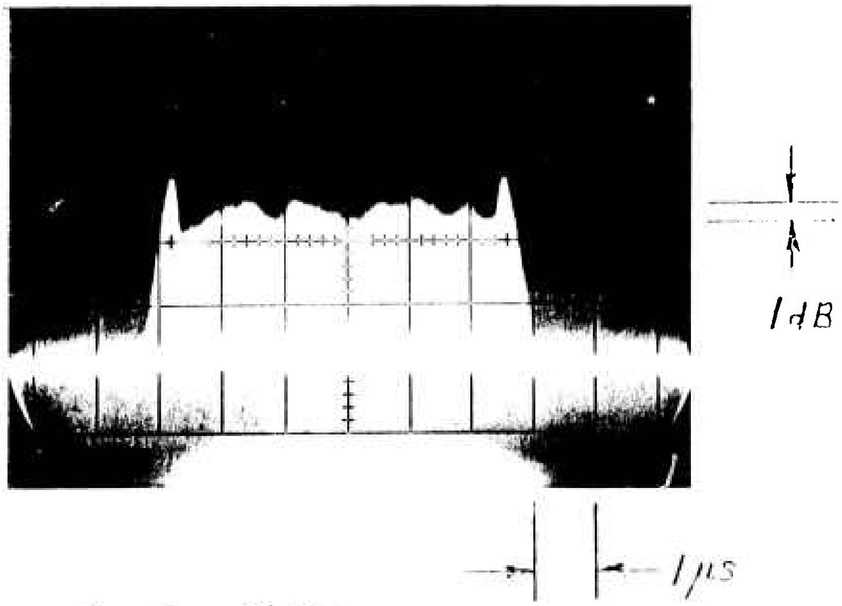
Narrow-segmented diodes

9 - 15 Ω-cm Bulk Silicon - No SiO_2

1300 Å Rails

Efficiency: -59 dBm @ 100 MHz.

FIG. 18--Interaction region uniformity.



$P_1 = P_2 = 16$ dBm

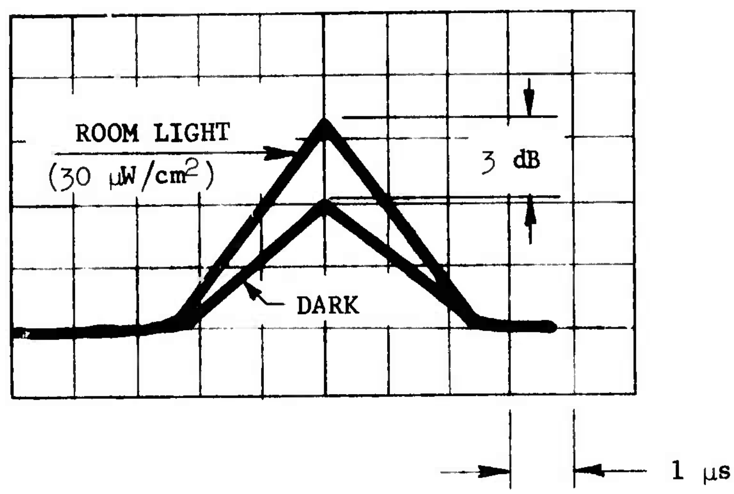
Wide-segmented diodes

15 Ω-cm EPI - 10 μ thick - SiO_2

1300 Å Rails

Efficiency: -63 dBm @ 100 MHz

FIG. 19--Interaction region uniformity.



$P_1 = P_2 = 12$ dBm

Narrow-Segmented Diodes

15 Ω-cm EPI 10μ thick

No SiO_2

1300 Å Rails - $F_{IN} = 100$ MHz

FIG. 20--Response to the light.

Using 30 $\mu w/cm^2$ of light, which corresponds to the intensity of room light, we observe, when operating the device as a convolver with two square pulses, that the output efficiency increases by 3 dB. As these experiments were carried out with a stripped surface, we might expect the junction to occupy most of the area. When the surface is illuminated, the electrons and holes are generated within the depletion layer, holes move to the p^+ region, and cause it to become more positive, thus decreasing the width of the depletion layer. This, in turn, causes the efficiency to increase. However, if the light intensity is still further increased, the efficiency drops because the diode is now forward-biased and its conductance shunts the diode depletion layer capacity so that very little rf voltage can be developed across it. Thus, we would expect, as will be shown in Section A.3, that the output would first increase with light intensity and then decrease. On the other hand, if a large portion of the semiconductor area was not within the depletion layer region, as is the case when the surface is oxidized, the generation effects within this region can also influence the output. In this case, there may be very little initial increase in output. Only the shunt resistive effect would be observed.

By changing the external bias applied to the system, we do not affect the voltage across the depletion layer itself, because this is set by thermal equilibrium conditions. We have shown that by changing the applied voltage we can, in fact, change the light sensitivity somewhat and produce a region where the output initially increases with light, or cause this region to be not present. Furthermore, by applying pulsed voltage which does affect the voltage across the p-n junction, we can increase the initial positive sensitivity region by applying the pulsed bias in such a direction as to increase

the depletion layer thickness. We can also eliminate this region by applying the bias in a direction to decrease the depletion layer thickness and cause it to be initially pulsed forward bias.

Another set of experiments using 50 Ω-cm epitaxial material is shown in Fig. 21. In this case, with a stripped surface the efficiency was - 50 dBm, a figure which compares very favorably with Gautier's best results on an airgap convolver. It can be seen in this case that there is only a slight increase in output power as the light level is increased. However, at relatively high light intensities, the output signal decreases by 20 dB and drops off as $1/g^2$, where g is the incident light intensity. This is the result of the theory given in Section A.3.

The basic aim of our experiments is, of course, to test the convolver as an optical transform device and to determine its definition. Recently, we obtained two dispersive delay lines from Lincoln Laboratories; a Hamming weighted compressor and an unweighted expander which have $2\frac{1}{2}$ MHz bandwidth and a delay time of 120 μsec. This corresponds to a time bandwidth product to 300 when unweighted, with a somewhat lower number of spots when weighted. Thus, we should be able to carry out transforms and inverse transforms of images with 200-300 resolvable spots. The device we have constructed has a total input bandwidth of approximately (sum of both transducer bandwidths) 60 MHz, with a delay time of 6 μsec, corresponding to 360 resolvable spots. Thus, the device performance should ultimately exceed the capability of the dispersive delay lines that we have available for carrying out the inverse transforms required.

Fig. 22 shows the experiment which is under way for testing the convolver resolution. At time $t = 0$, the center of the two 100 MHz chirp signals coincide with the middle of the convolver interaction region. The

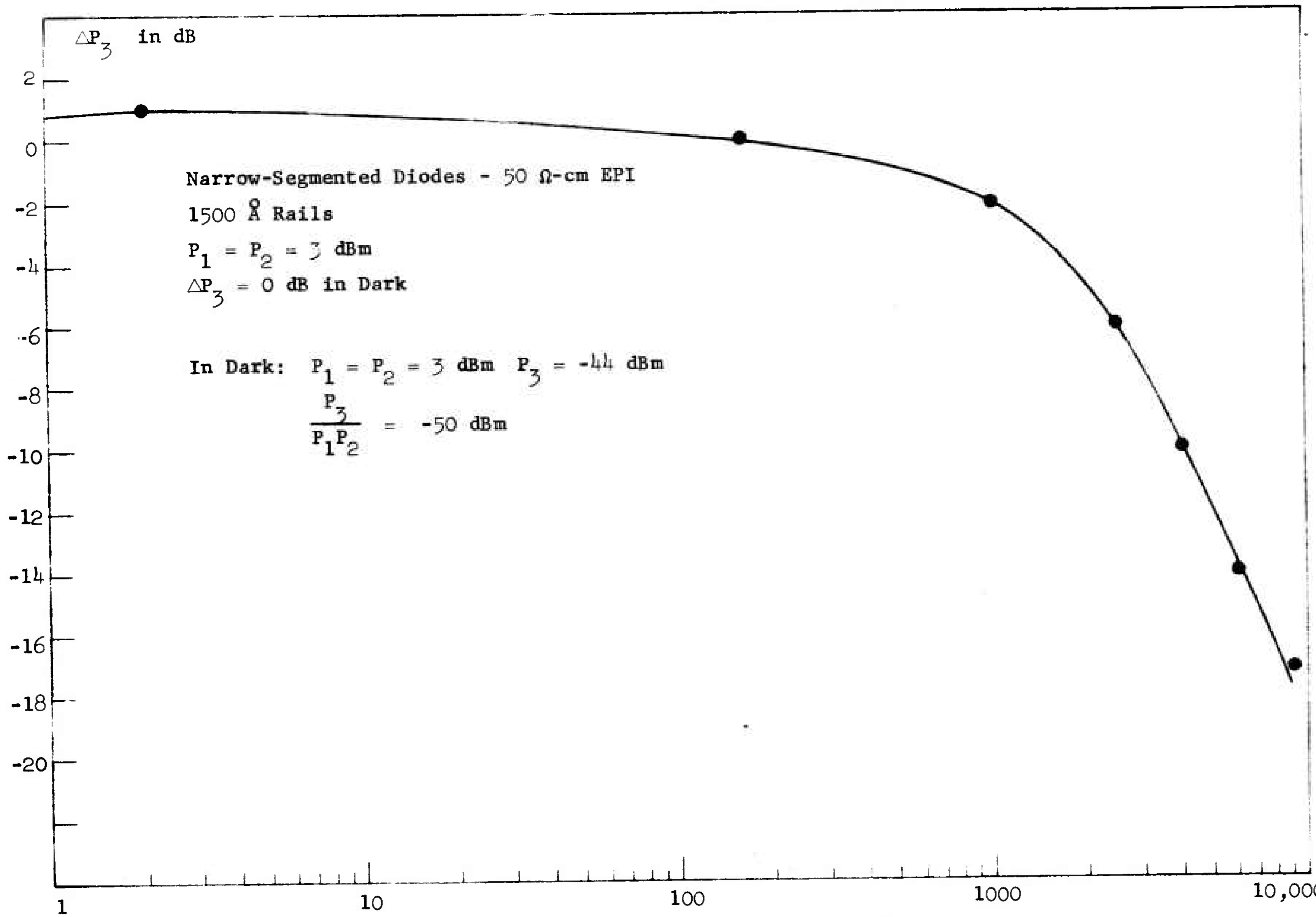


FIG. 21--Convolver response to light.

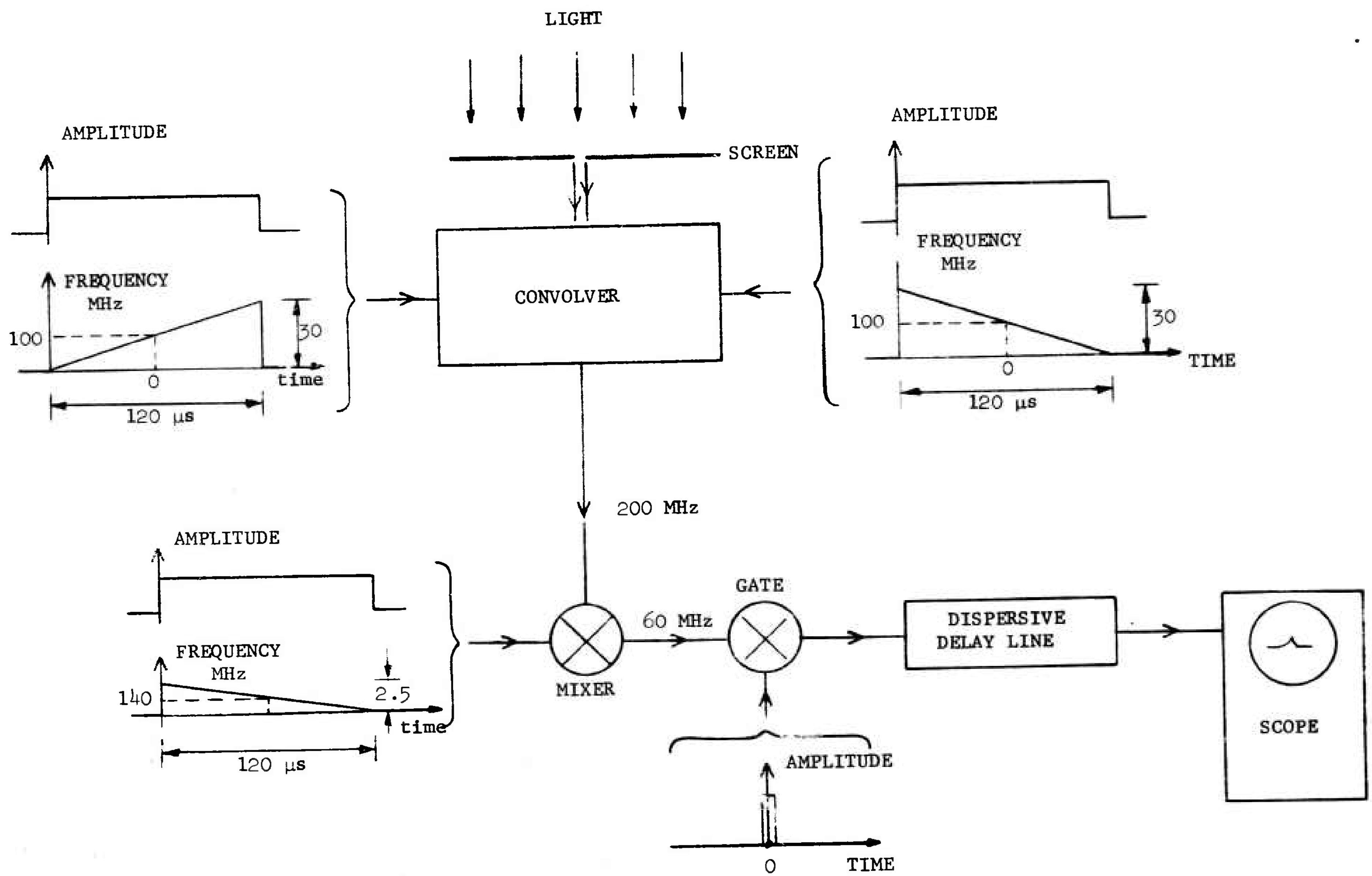


FIG. 22--Double Fourier transform experiment.

envelope of the convolver output signal is the spatial Fourier transform of the image focused on the silicon (for the time being a spot of light generated by the screen). A second Fourier transform is achieved by putting a chirp on the output signal matched to the dispersive delay line. Of course, the present screen will be replaced by an appropriate grating when checking the resolution. The gate allows removing the dc component of the image signal. So far, because of the nonuniformity of the structure, we have measured a resolution of 120 points.

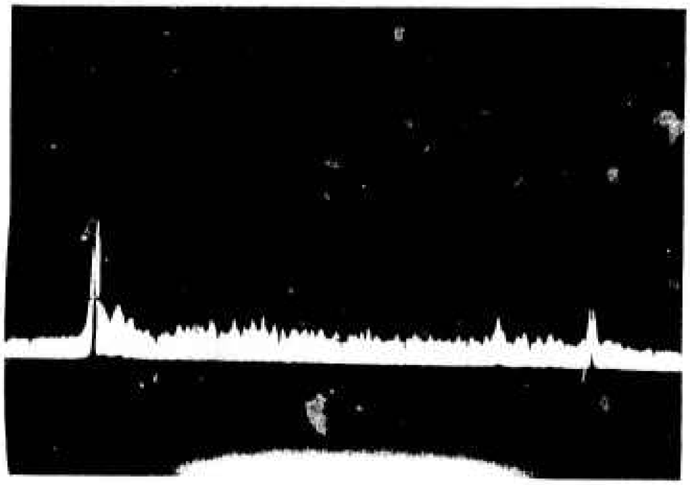
We have carried out initial experiments and are continuing them at the present time to demonstrate the capabilities of this optical imaging device. We have changed the configuration somewhat from the earlier experiments of Gautier.[2] We are now concentrating exclusively on taking Fourier transforms of the optical image. This is done with the circuit shown in Fig. 22. Two FM chirp signals are inserted into each end of the device respectively; one being a chirp whose frequency increases linearly with time; the other, the similar chirp with a frequency that decreases with time. As we have shown previously, this implies that the output of the device would be the spatial Fourier transform of the illumination along the length of the device. By taking this output signal and using it to modulate a chirp with a 2.5 MHz bandwidth, i.e., mixing it with such a chirp, and inserting the mixed signal into the dispersive line, we can obtain the inverse Fourier transform and, hence, reproduce the illumination along one line of the image.

As we have discussed previously, the dynamic range of the devices is limited by the ratio of the output with illumination to the output without illumination. In one case, we have seen that this can be as much as 20 dB; in others, it is only of the order of 3 dB. However, the dark current,

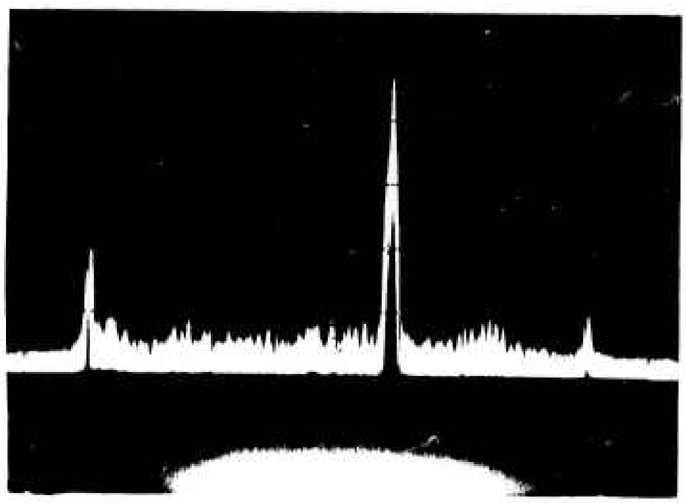
or the output in the dark, is basically relatively uniform over the length of the device. Hence, we might expect that its Fourier transform corresponds to a low spatial frequency component. This occurs at a specific time T. By gating the output, as shown in the circuit of Fig. 22, to eliminate this spatial frequency component, we can essentially eliminate the dark current and thus obtain a much larger dynamic range. Furthermore, we might expect that such a procedure would also eliminate signals due to background illumination. Such a result would be of great importance for infrared imaging where the background intensity is normally relatively high.

We have carried out initial experiments to test the transform properties of the device in this manner. In Fig. 23 we show the change in with the output from the dispersive delay line when the device is illuminated with a small spot of light. This result was taken with a convolver device with approximately 20 dB dynamic range. It will be seen that the transform system operates very satisfactorily.

A second set of results is shown in Fig. 24. The first shows the output from the dispersive delay line when there is no illumination present. Then, with a short gate pulse applied to the direct output from the device, we observed that the output level is considerably decreased by a factor of approximately 10 dB. When uniform illumination of light is applied to the device, very little change in output is observed. This is because we are cutting off the low spatial frequency components of the light. Thus, we tend to eliminate background illumination. Finally, when a spot of light is applied to the device, there is an increase in output in a narrow region. The results shown here are extremely crude, because the high resistivity device used for the experiment is not very



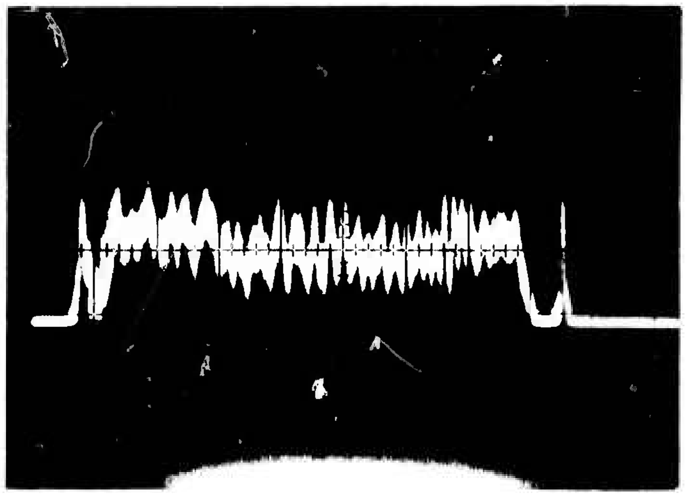
(a) — 20 μs



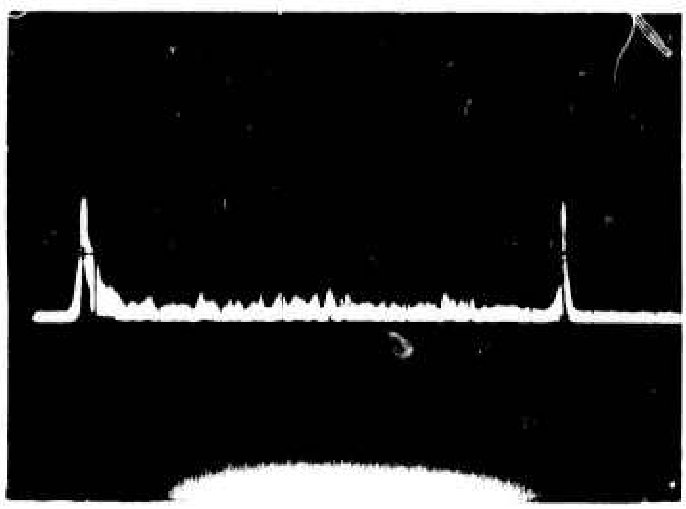
(b)

FIG. 23--Double Fourier transform experiment;

(a) no light present,
(b) spot of light present.



(a)



(b)

FIG. 24--Double Fourier transform experiment; no light

(a) not gated;
(b) gated.

uniform. Thus, the increase in dynamic range we can obtain by this procedure is, at the present time, very limited because of the lack of uniformity and the higher spatial frequency compponents that are present in the output.

We intend to work on improving this nonuniformity and eliminating internal reflections within the device. We believe that, as we clean up the system, we should obtain large dynamic range by this simple gating procedure. However, we will also return to the use of illumination through a grating with two different input frequencies at each end of the device to obtain a large dynamic range.

We can conclude, however, that the results we have obtained are extremely encouraging for they indicate that the p-n junction concept is a valid one, that the mechanical supporting techniques that we have devised are performing extremely well and reproducibly. This is a technique which is, of course, applicable to all kinds of convolvers and storage devices. We note that the Fourier transform concepts, when applied with large bandwidth devices, are valid ones which are performing as predicted. The filtering concepts used are, of course, applicable to making variable bandpass filters whose properties can be changed at will.

3. A Theory for the Light Sensitivity of p-n Junction Convolver

We give here an outline of the theory we have developed to determine the light sensitivity of a p-n junction or Schottky barrier type of convolver, where p-n junctions or Schottky barriers are laid down along the length of the semiconductor. The theory predicts reasonable sensitivities for this type of convolver and results which, qualitatively and to some extent quantitatively, appear to agree with out initial experiments on

these devices.

We take the point of view that the diode is normally at the thermal equilibrium potential. If a dc potential is applied to external electrodes through the capcitance of the $LiNbO_3$ substrate, the diodes will still remain at their equilibrium potential. This is because the leakage current in the diode will always compensate for any external potential applied through a capcitor. On the other hand, in the more general situation of a ZnO on Si convolver, there may be some leakage through the ZnO, and therefore the equilibrium potential of the diode can be affected by external potentials. However, we shall only deal with the simplest case here to give the reader some insight into the physics of the problem.

When the diode is illuminated, holes and electrons are generated in the depletion layer. Holes move to the p^+ region and electrons move toward the bulk material, the n-type region. The holes and electrons are assumed to move rapidly to these regions, because of the high internal fields in the depletion layer. The holes that move to the p^+ layer, and the electrons moving to the n layer cause the p^+ layer to become more positive with respect to the bulk material. Thus, the voltage across the diode changes and it becomes forward biased. The equilibrium point is reached when the forward bias current density I equals the reverse current generated optically within the junction. If the generation rate of carriers per unit area is G, then the current per unit area due to illumination is qG, where q is the electronic charge. It is shown by Sze[3] that, typically, in an Si diode, the forward bias current is determined by recombination within the depletion layer, rather than by diffusion current in the bulk. Therefore, we can use the normal formula for

forward bias current and wirte

$$qG = I = \frac{q\ell n_i}{2\tau} e^{qV/2kT} \tag{1}$$

where ℓ is the length of the depletion layer, n_i is the intrinsic carrier density, V the external voltage across the junction, τ is the recombination time of carriers within the depletion layer, k is Boltzmann's constant, and T is the temperature.

The basic reason for the change in convolver efficiency under these conditions is the fact that, as the voltage across the diode changes, the width of the depletion layer changes. This, in turn, changes the efficiency of the convolver and typically causes it to increase as the depletion layer thickness decreases. However, beyond a certain point, as the forward current increases, the dioe rf resistance begins to decrease so that this resistance shunts out by the diode capacity, the nonlinear varactor capacity which causes the interaction between the two acoustic surface waves entering the device. Thus, eventually, the effect of this shunt resistance is to tend to short out the diode and cause the convolver efficiency to decrease. Therefore, with weak illumination, we expect an initial increase in efficiency and then, as the illumination becomes stronger, the efficiency should decrease and the output power can change by relatively large values of 20 - 30 dB.

Following this line of reasoning, we determine the built-in potential V_b across the depletion layer. This is

$$V_b = \frac{kT}{q} \ell n \left(\frac{N_d N_a}{n_i^2}\right) \tag{2}$$

where N_d is the doping density of the n-type region and N_a is the doping density of the p^+ layer. It follows from Eqs. (1) and (2) that the external potential V across the diode, which determines its capacity and its thickness is

$$\frac{V}{V_b} = \frac{\ell n\left(\frac{2\tau G}{\ell n_i}\right)}{\left(\frac{\sqrt{N_a N_d}}{n_i}\right)} \tag{3}$$

where the internal potential across the depletion layer is $\phi = V_b - V$.

We can work out a simple equivalent circuit for the system as shown in Fig. 25. In this circuit ϕ_a is the rf potential due to the acoustic surface wave, C_{gap} is the capacity across the gap between the semiconductor and the piezoelectric substrate where all quantities are given for a unit area. In the simplest terms, this capacity is $C_{gap} = \epsilon_0/h$, where h is the gap width. C_{gap} can be expressed more precisely for all values of the parameters; this has been done by Gautier[2] and Shreve.[4] C_{dep} is the depletion layer capacity. This capacity per unit area is ϵ/ℓ, where ϵ is permittivity of the semiconductor and Y is the rf conductance of the **semiconductor** defined as

$$Y = \frac{\partial I}{\partial V} = \frac{qI}{2kT} = \frac{q^2 G}{2kT} \tag{4}$$

Thus, this conductance increases with illumination, as might be expected.

We see that under illumination the depletion layer capacity decreases because if is of the form

$$C_{dep} = \frac{\epsilon}{\ell} = \sqrt{\frac{\epsilon q N_d}{2(V_b - V)}} \tag{5}$$

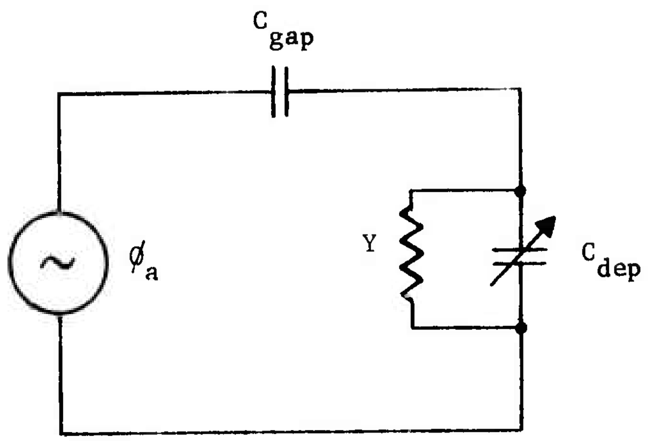


FIG. 25--A simple equivalent circuit for the system.

The convolver itself is a nonlinear device because this depletion layer capacity is, in turn, nonlinear. In terms of the usual convolution theory, the output voltage due to nonlinear interactions, is proportional to the square of current I' passing through it. With two incident waves, it is proportional, then, to the product of the currents. Thus, the output power from the device increases as I^4. It is apparent, then, that in order to obtain optimum sensitivity, the current through this circuit must be as large as possible and, when the device is illuminated, the effect of a change in C_{dep} must be as large as possible. This implies, in turn, that we require C_{gap} to be as large as possible. Typically, the gap is of the order of 1000 Å thick, but has a relative permittivity of 1, whereas the depletion layer thickness is of the order of 1 μm , but has a relative permittivity of 12. Thus, the two capacities are quite comparable, and so even a change in the depletion layer capacity by a factor of ten to one only gives a few dB's change in the output from the device. Thus, we would expect that, on the basis of the variation of the depletion layer capacity alone, the output would only vary by a few dB . In our devices the estimates lead to a variation in output of approximately 3 dB at best.

It will be seen that, as the illumination is increased and admittance due to the forward current becomes comparable to that of the depletion layer capacity; now the output power will decrease as the voltage across the depletion layer decreases. With these estimates in mind, we have calculated parameters for 15 Ω-cm material with p-n junctions laid down on it. These predict that the conductance across the depletion layer becomes comparable to its capacitive admittance at power levels of the order of 300 $\mu w/cm^2$; numbers in reasonable agreement with our results for such

materials. We predict that the total increase in output power in this situation will be approximately 3 dB. Beyond that point, as the admittance becomes very large, the output power varied as $1/Y^2$, $1/G^2$; a result in good agreement with our experiments as shown in Fig. 23.

It is apparent that, from this simple theory, it would be desirable to increase the gap capacity relative to the depletion layer capacity. This is not simple to do in an airgap device. Strip coupled devices, however, have the property that the effective gap capacity is much larger than the depletion layer capacity, because the diodes are relatively small in area compared to the area from which acoustic excitation is taken. We are constructing devices of this kind of ZnO on Si configuration to test this hypothesis. We are also experimenting with early strip coupled devices made by Shreve,[5] which use mechanical contacts from the strips to the semiconductor. We are changing the semiconductor region for Schottky barrier devices or p-n junction devices, so as to determine whether these principles are, indeed, valid ones. At the same time, we believe that the same principles are valid for storage types of devices. The storage time of a signal induced on the depletion layer is obviously much larger if there is a shunt gap capacity across it which is very large. Again, the strip coupling principle has this advantage and will be tested for this purpose.

B. ZnO on Si Devices

1. Introduction

The work of B. T. Khuri-Yakub, which was partially supported on this contract, and on a RADC contract, has resulted in a thesis, "The Application of Zinc Oxide on Silicon to Surface Acoustic Wave Devices". An abstract on this thesis is given below. It is available as an internal technical report ML 2509.

ABSTRACT

In this work we are interested in the wide bandwidth excitation of surface acoustic waves on silicon, and their use for nonlinear parametric interaction applications. We use zinc oxide, a piezoelectric material deposited in a vacuum, to excite the surface acoustic waves.

The fabrication of rf sputtered zinc oxide transducers on bulk wave delay lines and for use in surface wave acoustic convolvers and surface wave amplifiers on silicon will be described.

The optimum temperatures and conditions of growth for sputtered zinc oxide films on a variety of substrates were found and checked by reflection electron diffraction, scanning electron microscopy, and acoustic measurements. Results obtained are very consistent from run to run and have been verified by the construction of a large number of bulk delay lines and surface wave delay lines.

We used the piezoelectric interdigital transducer to excite surface acoustic waves. We have determined the important parameters in the electrical equivalent circuit of the interdigital transducer, and demonstrated excellent agreement between our theoretical expectations and experimental results; we did this by making input impedance measurements on a large number of transducers. We have used these results to design and construct a new type of tuning network that allowed us to obtain

a 20% fractional bandwidth on the input transducers. Due to the presence of the silicon, a new type of transducer was made possible, the diffusion layer transducer. This kind of transducer has the advantage of being light and bias sensitive. We have derived the theory of operation of such a transducer, and demonstrated its basic principle of operation.

We have used the monolithic zinc oxide on silicon structure to construct acoustic convolvers to perform signal processing experiments. A complete theory for the variation of convolution efficiency with bias and device parameters was developed. This theory takes into account the condition of the surface of the silicon; we observed that maximum convolution efficiency occurs when the surface of the silicon is in depletion. We have designed and constructed many convolvers, and observed a reasonable agreement between theory and experimental results. The presence of fast bulk traps in the zinc oxide was identified to explain the presence of a new storage phenomenon, and the change between the predicted and observed variation with bias of the convolution efficiency.

Monolithic waveguide convolvers were constructed, and improvement in convolution efficiency was observed, as predicted by our theoretical calculations.

2. Development of ZnO Station

A considerable effort has been made to construct a new dc ZnO deposition station, using the latest techniques developed at Stanford, at Hughes, and Bell Telephone Laboratories. This station should have the advantage of stability, and easier cleaning than is possible in our present rf station. Our initial results with this station are encouraging, but considerable effort is still required before we can use it for our convolvers.

We need to map out the correct regimes of operation for optimum deposition on silicon and on the gold pads that we require. We have, indeed, made good volume wave transducers in this station, but the system has not yet been optimized for surface wave use. Therefore, for the next few months, we will continue to use the rf station, which is now operating very satisfactorily. The dc station will continue to be developed on another contract concerned with the acoustic microscope, where the need is greater.

3. ZnO on Si Schottky Barrier and p-n Junction Devices

We have carried out some initial tests on Schottky barrier devices laid down in the Si underneath the ZnO. The initial tests were carried out by P. Borden, who is working under Joint Services and NSF sponsorship. These results are extremely encouraging. They appear to indicate that, because of the slight leakage current of the Schottky barriers, the internal dc potential in the diode remains at the thermal equilibrium value, and so no deleterious effects due to the presence of traps in the ZnO occur. The devices no longer exhibit hysteresis, as our earlier devices did, and relatively long time storage in the storage device mode can be obtained with these Schottky barriers. Storage times of as much as 100 msec have been observed, with read in times in the tens of nanoseconds range. We, therefore, believe that we have conquered the main stumbling block in the use of ZnO on Si convolvers, for these convolvers have operated with reasonable efficiencies comparable to the convolvers we have made on bare Si.

We have also carried out some initial tests of the illumination efficiency of these convolvers; they have fairly poor sensitivity because the platinum silicide Schottky barriers themselves are relatively thick

and, therefore, only a few percent of the light reached the actual depletion layer region. In addition, the theory that we have already given would appear to indicate that p-n junctions, rather than Schottky barriers, should be far more efficient when used as light-sensitive convolver devices. This is because for a given generated current, the potential in a Schottky diode is less than in a p-n diode made on the same n-type substrate. Under these conditions, again no hysteresis due to the presence of light was observed. This is a highly desirable consequence, and of great importance in making ZnO on Si convolvers practical.

We are now constructing devices on this contract using layers of p-n junctions, or Schottky barriers, laid down underneath the ZnO. Our initial experiments are aimed toward making a two dimensionally scanned device. First, we will make such a device as shown in Fig. 26, illuminated through a grating, which has a period equal to the acoustic surface wave wavelength.

As a second step, our intention is to construct a device approximately 1 cm square in which acoustic surface waves will be introduced at angles of 90 degrees to each other. If we suppose that these waves have the same frequencies and propagation constant $k_x = k_y = \omega$ the resultant potential generated at the surface of the semiconductor, on which a square array of junctions is laid down, has a frequency 2ω, and propagation constant $\underset{\sim}{k} = \underset{\sim x}{a} k_x + \underset{\sim y}{a} k_y$ where $\underset{\sim x}{a}$ and $\underset{\sim y}{a}$ are the unit vectors in the x and y directions respectively. Such a signal will interact to give a uniform potential output, if the device is illuminated through an optical grating whose pitch is $1/\sqrt{2}$ of the wavelength of either acoustic surface wave, and is laid down at an angle of 45° to the axis of propagation of either wave.

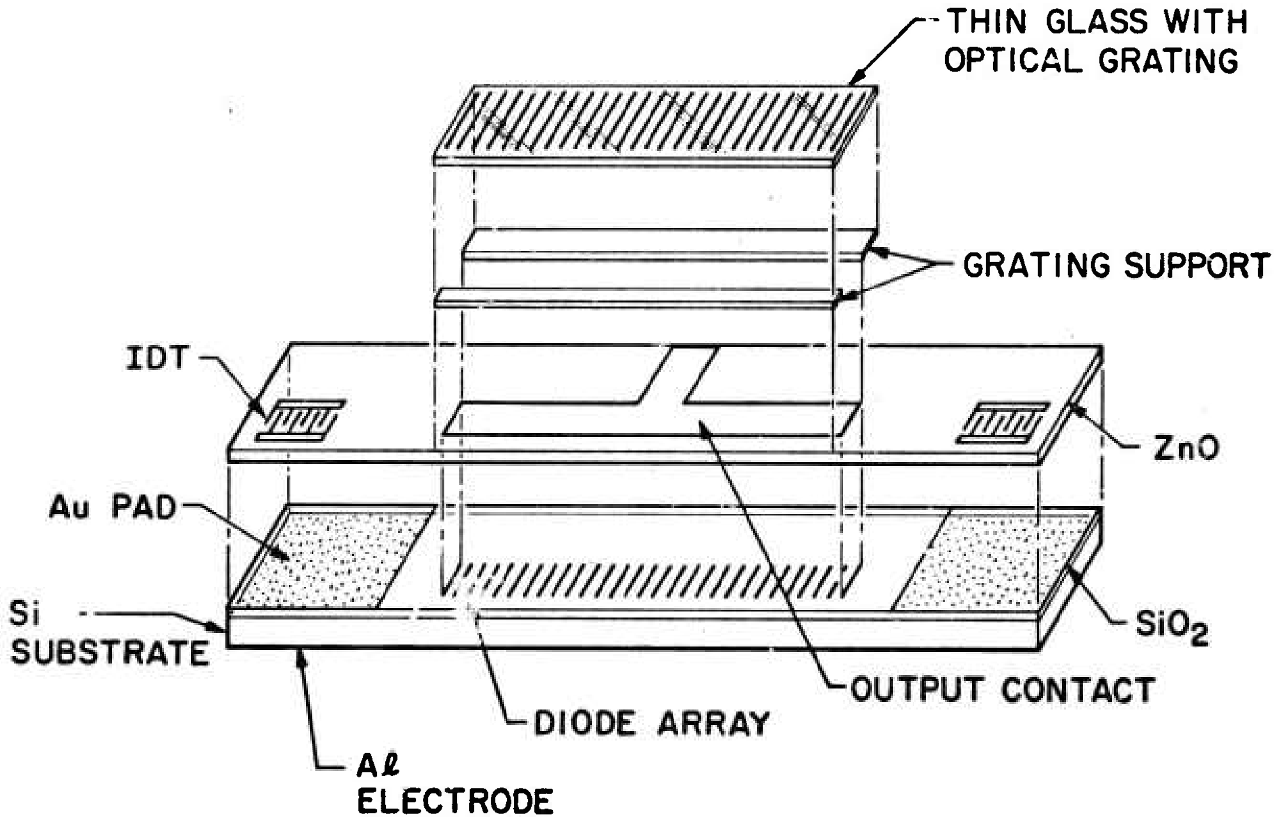


FIG. 26--A one-dimensional optical imaging device using ZnO on Si and illumination through a grating with a period equal to the acoustic wavelength.

By using pulsed input signals, such a device will scan the surface of the semiconductor along the 45^{o} line where the two pulses intersect. By changing the delay time between pulses, it is then possible to scan out a complete raster. More importantly, if the input signal in the x direction is a linear FM chirp, the signal in the y direction a constant frequency ω_y, the output will be the Fourier transform in the x direction of the spatial frequency component of the illumination in the y direction corresponding to the spatial frequency ω_y, when in the presence of the grating filter. By repeating this process for different values of ω_y, we can carry out a complete two dimensional transform of the optical image. In this case, the output would be equivalent to a raster scan of the two dimensional transform of the optical image, with the raster lines essentially parallel to the x axis, as in a normal TV picture. Here we vary ω_x rapidly to provide the line scan of the Fourier transform in the x direction, and vary ω_y slowly to provide the frame scan of the Fourier transform in the y direction. We would hope to reconstruct the original image, in a convolver device, based on the same principles. It should be noted that, because of the two dimensional nature of such device, the storage density should be extremely high, and, eventually using bandwidths of the order of 100 MHz, it should be possible to store 10^5 bits of information in a square centimeter in devices of this kind. We will begin to construct such two dimensional devices, after proving out our initial concepts on the simpler linear array.

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